Leveraging Peer Production

for a

Green Growth Economy

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List of Abbreviations

API	Application Programming Interface
CBPP	Commons-based peer production
DA	Delegated act
DLT	Distributed ledger technology
DPP	Digital product passport
EA	Economic actor
ESPR	Ecodesign for Sustainable Products Regulation
FCOS	Fab City Operating System
fsQCA[1]	Fuzzy-set Qualitative Comparative Analysis
GGEPP	Green growth economy that leverages forces of peer production
HD	Hardware documentation
LOSH	Library of Open Source Hardware
OS	Open source
OSH	Open source hardware
OSHD	Open source hardware documentation
PPC	Peer Production Coefficient
QCA	Qualitative Comparative Analysis
TC	Transaction cost
UI	User interface

[1] QCA and fsQCA are used interchangeably, except for chapter 2.

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Terminology

Fab Lab

A Fabrication Laboratory (Fab Lab) is an open workshop that focuses on digital manufacturing such as 3D scanners, 3D printers, laser cutters and other CNC machinery. Since with computer-controlled machines it becomes relatively easy to fabricate complex geometries, a Fab Lab enables one to make almost anything (Gershenfeld, 2005, 2012). Fab Labs are typically non-profit and have low-threshold entry levels. Within around two decades, more than 1750 Fab Labs worldwide have come into existence (Fab Foundation, 2025).

Peer production

The definition of peer production is elaborated on in chapter 5.1.

Ecodesign

Ecodesign includes ecological requirements in product development goals. There is a consensus in literature that it entails three dimensions: 1. Design and development of products, 2. Effort of reducing the environmental impact of these products, 3. The complete product life cycle is taken into account (Schäfer & Löwer, 2020). The EU Commission's (2022, p. 2) ESPR defines the pursuit of ecodesign as follows:

> ...improve product durability, reusability, upgradability and reparability, improve possibilities for refurbishment and maintenance, address the presence of hazardous chemicals in products, increase their energy and resource efficiency, reduce their expected generation of waste materials and increase recycled content in products, while ensuring their performance and safety, enabling remanufacturing and high-quality recycling and reducing carbon and environmental footprints.

This study adheres to this understanding of the term ecodesign.

Artefacts

Artefacts are what in the conventional economy would be products. However, in the peer production realm oftentimes the actual “product” is not marketed. Therefore, in the understanding of the author, it is misleading to use the term product for the result of peer production. The term “artefact” is economically more neutral and is used in this sense by Redlich et al. (2015).

Open Source Hardware

The Open Source Hardware Association (2023) defines Open Source Hardware (OSH) as:

> …hardware whose design is made publicly available so that anyone can study, modify, distribute, make, and sell the design or hardware based on that design. The hardware’s source, the design from which it is made, is available in the preferred format for making modifications to it. Ideally, open source hardware uses readily-available components and materials, standard processes, open infrastructure, unrestricted content, and open source design tools to maximise the ability of individuals to make and use hardware. Open source hardware gives people the freedom to control their technology while sharing knowledge and encouraging commerce through the open exchange of designs.

This definition is an analogy of the open source software definition. This study highlights the fundamental differences in the economic characteristics of open source hardware and software. The focus of this study lies in the collaborative development of the documentation of source available hardware, which is hardware that has a publicly available documentation that entails all information necessary to rebuild the hardware. Typically, the documentation would consist of the materials composition, instructions for disassembly, but also software for upgrade, updates and more.

Source Available Circular Economy

In the Source Available Circular Economy (SACE), data is not open in the sense that it or its derivatives can be used for commercial purposes without restriction. So, the data can be displayed by anyone but commercial exploitation of it must be permitted by the one owning the right of the digital asset. The distinction between source available and open source is an analogy from a common practice of distinction in the realm of software licensing.

Commons

Commons are shared resources which are co-governed according to a community of users and their rules (Bollier, 2014). The study of common property regimes, or “commons” has been intensively conducted by Elinor Ostrom (1933-2012). She has empirically proven that common property regimes can be sufficient to allocate resources in a way that overall wealth is maintained or even enhanced. She hence positioned common property regimes as viable alternatives to market and planned economies. She was awarded the Nobel Memorial Prize in Economic Sciences in 2009, in response to the apparent failure of causal economic science at that time of economic crisis.

Digital Commons

Digital Commons are commons in the digital realm. Elinor Ostrom received the Alfred Nobel Memorial Prize in Economic Sciences in 2009 for her scholarly work on the commons, as outlined in the previous clarification of the term commons. With the widely spread access to tools enabling access to the internet, the phenomenon of digital commons has emerged. One of the most prominent examples of it is Wikipedia or Free and Open Sources Software (FOSS).

Federation

Federation describes a software’s backend architecture that relies on multiple servers, not just one. Usually, each node of the network hosts at least a copy or a share of the overall system. This decentralisation of the software’s backend architecture increases reliability and distributes power.

Digital Sovereignty

Digital Sovereignty is a term made popular by Bria (2017). She frames it in opposition to dependency on big-tech. Hence digital sovereignty describes a situation where the digital means of production are in the hands of those who use it. These means can be servers, but also the capacity to maintain and develop software that is substantial for the functioning of societies, and with it, economies.

Token

A digital asset that verifies ownership of a physical good. In the context of this study, a "token" is a digital representation of value or a specific asset related to sustainability and resource management. It can be used to track, trade, or incentivise various activities that promote a circular economy.

1. Introduction

The 13th of June 2024 marked a historic day in the endeavour of preserving earth for generations to come. On that day, Roberta Metsola, president of the European Parliament, and Hadja Lahbib, representing the European Council, finally signed Regulation 2024/1781. This regulation establishes a framework for the setting of ecodesign requirements for sustainable products. It sets minimum requirements for almost all products sold on the EU market which includes a digital product passport (DPP) that provides businesses, governments and consumers with information on a product's environmental performance. Recycling and repairing, i.e. a circular economy, will be enhanced and hazardous substances will be tracked throughout the supply chain. In other words, DPPs will carry documentation of products regarding information on how they are made. Although the exact configuration of the regulation and the passport will only successively be defined in several delegated acts (DA), it is of specific interest for this study that it is already clear that a certain degree of openness of product data will be enforced.

While there is a growing strand of research shedding light on ecodesign and DPPs (e.g. Walden et al., 2021; Adisorn et al., 2021; Jensen et al., 2023; Langley et al., 2023; Psarommatis & May, 2024), there is a lack of research on the effect opening up production data of hardware through DPPs has on the structure of economies. The degree of openness of production data, which is a significant aspect of transaction costs, is likely to affect the granularity of value creation. For example, if product data that is necessary for repair and recycling becomes open, it is more likely that economic actors other than the original producers repair or recycle the product. In fact, recital 28 of Regulation (EU) No 2024/1781 lists this as one of its rationales. Thereby, value creation becomes more granular or distributed. The study of this cause and effect relation is part of the subject of transaction cost economics (TCE) (Coase, 1937; Williamson, 1975; Williamson, 1985; Benkler, 2002). In TCE theory, the economic structure changes along with the transaction costs, such as transaction fees, transportation cost, or any other friction for economic transactions, i.e. the cost of transactions.

Benkler (2002) argues that if the transaction costs in information production (for example software, encyclopaedia articles) become very low, peer production emerges. In peer production, the granularity of the structure of value creators is very high. Even individual peers can participate in the production of free software or Wikipedia articles, because it essentially only takes a laptop with internet access to participate, i.e. the transaction cost is very low. In his article, Benkler is explicit that his claims only regard the intangible realm such as information production, as Spaeth et al. (2010) shed light on. Regardless, there are research streams and practices that attempt to leverage the forces of peer production or digital collaboration in general beyond the digital realm, namely into the value chain of hardware. Kostakis et al. (2015b) call production in makerspaces a kind of peer production in some regard. The research string around the P2P Lab, in which research by Kostakis and Bauwens (2014) and Kostakis et al. (2013) is conducted, appears to push most consistently for the explicit peer production of hardware.

One of the most systematic attempts to put the idea of leveraging the forces of peer production and digital collaboration in general into practice is the Fab City Network, which originated from the Fab Lab Network and the P2P Lab, and today consists of more than 45 cities, regions and countries worldwide. The foundational Fab City idea is that globally distributed economic actors collaborate on open source hardware documentation, that is then transferred into physical goods in local - mostly standardised and digital - manufacturing. The increased openness of designs is supposed to enhance ecodesign and eventually decouple economic growth from resource consumption, which Perez (2015) considers green growth.

A premise for the intended broad implementation of the Fab City idea is that peer production or digital collaboration of hardware can be at least partly competitive to the currently dominant modes of production and the linear economy. According to TCE, peer production only emerges if the conditions are more favourable for it than any other economic governance arrangement. The opening up of production data that follows the Ecodesign for Sustainable Products Regulation (ESPR) could make conditions more favourable for peer production to emerge. Here, the openly accessible production data would enable digital collaboration across the value chain of hardware, meaning from the design to the manufacturing, repairing and reuse of materials. One reason why it is problematic to assume that principles known from peer production of digital information apply similarly in the realm of hardware, is that hardware and software have fundamentally different economic characteristics. Hence, the key question at this stage is: 'To what extent does peer production of hardware occur compared to inherently digital goods such as software?' This serves as the first research question (RQ1) of this study.

To justify the focus on RQ1, the author’s experience working in multiple roles in Open Source hardware (OSH) and Open Source (OS) software development from the years 2019 to 2023 will be reflected on.

To further justify RQ1 through practical experience, the following reflects on experience from the years 2019 to 2023 in which the author of this study had multiple roles in Open Source hardware (OSH) and Open Source (OS) software development. For example, there was an insightful engagement at Open Source Ecology (OSE) in 2019. OSE is an organisation that aims at developing an Open Source Village Construction Kit. There are several branches of OSE worldwide. The author mainly engaged with the American branch, where OSE originated, and the Belgian branch. The case of OSE has been dealt with in literature (Moritz et al., 2016). As its main digital infrastructure, OSE uses a Wikimedia which it complements with Google Sheets and Google Slides. The author’s participation in OSE focused on the development of an Open Source 3D printer (Fused Deposition Modelling). As part of that, OSE organised a simultaneous multi-site workshop. Hereby, and through engagement with OSE in general, the following problems became apparent:

- In the workshop, only the participants present in Ghent, Belgium, and those present in the US managed to build the 3D printer up to the point that it could print. Remote participants did not manage to do so, at least during the time of the workshop.

- High fluctuation among peers.

- Extremely concentrated distribution of workload across time (founder did almost everything).

When first engaging with OSE and similar initiatives, one is reminded of experience with Wikipedia or other peer production information projects. But digging a little deeper reveals that the distributed production of hardware is subject to much more friction compared to the collaborative production of digital information.

Another justification for this research is the author's experience in co-founding and residing as the chairman of the board of Fab City Hamburg[2] where it was his daily practice to make distributed production of hardware, fuelled by open production data, a reality. Here, the transaction costs for the global and even local distributed production[3] were enormous. There were language barriers, insufficient standardisation, silos of communication due to different communication channels and so on. As explained above, TCE predicts that high transaction costs favour other economic governance regimes over digital mutual coordination.

One early insight from the time of practice was that at the different phases of the value chain the conditions for a realisation of the vision differed. This is obvious when comparing the phases of the creation of a digital design with the phase of manufacturing a design in terms of its chance for distribution. It is much less costly to have peers across the globe collaborating on the creation of a digital design than having them collaborate on the manufacturing of a physical item. In the former case, collaboration could be channelled by exchanging CAD files over the internet whereas in the latter case, the peers would either themselves have to travel

[2] As the representative of the Helmut-Schmidt-Universität / Universität der Bundeswehr Hamburg.
[3] Distributed production means that the production is not conducted at one place or by one organisation, but rather at a multitude of sites and by a multitude of peers.

to each other or send each other physical components at a comparably high cost. This exemplifies that at different phases of value chains of hardware with open production data, the conditions for economic governance arrangements change. Therefore, research question 2 (RQ2) asks: 'What is a suitable economic governance in phases along a product's value chain where the forces of peer production are leveraged for a green growth economy?'

This study is grounded in the Techno-Economic Paradigm Shift (TEPS) theory. This theory explains economic and technological development as interrelated and progressing in cyclical patterns, where each cycle lasts around half a century or more and constitutes a Techno-Economic Paradigm (TEP). Each TEP can manifest a golden age that entails an overall wealth surplus (see Perez, 2002, 2010). It is argued that for the current ICT TEP to reach a golden age, green growth is essential, which means the decoupling of economic growth from resource extraction (see Perez, 2015). It has been emphasised that peer production forces are crucial for reaching a golden age of the ICT paradigm (Kostakis, 2013; Kostakis et al., 2015a). The knowledge about the extent to which peer production of hardware exists (RQ1) and which economic governance is suitable in each phase along the value chain of hardware forms the foundation to approach the contours of an economy that leverages the forces of peer production for green growth. More specifically, RQ3 asks: 'To the extent that peer production of hardware can exist, what would an economy look like that leverages this potential for green growth?'

With the TEPS framework, it is possible to outline how the potential of peer production for green growth can be leveraged at the intersection of governance and technological development. This is applied by presenting a digital infrastructure by the name of "Fab City OS" as one example. As the TEPS framework highlights the significance of finance for transition, how finance could play a significant role in this context is elaborated on.

Research Questions:

1. To what extent does peer production of hardware occur compared to inherently digital goods such as software?

2. What is a suitable economic governance in phases along a product's value chain where the forces of peer production are leveraged for a green growth economy?

3. To the extent that peer production of hardware can exist, what would an economy look like that leverages this potential for green growth?

4. Adopting the TEPS framework, what are effective approaches for a transformational path to leverage the forces of peer production for a green growth economy in the ICT paradigm in the context of the European Green Deal?

2. Methodology

The aim of this chapter is to explain how this exploratory study's methodology is suited to attain answers to the research questions developed above. Since the studied subject is new, qualitative research is appropriate because it helps to generalise outputs and provides an overview (Stickel-Wolf & Wolf, 2009). In supplement, data from projects of digital collaboration is attained and analysed with fuzzy-set Qualitative Comparative Analysis (fsQCA) to support answering research question 1, 3 and 4. A literature review is conducted to reflect two essential findings of this study in scientific literature. Since fsQCA and literature reviews conducted in this study can at least partly be considered quantitative, this study also has quantitative elements.

Carlota Perez's (2002, 2009 & 2010) TEPS theory serves as the theoretical framework for this research. The TEPS theory is based on the premise that economic and technological advancements are interrelated. Therefore, it is a sound framework because the topic of how peer production can be used to enhance green growth touches the fields of technology and economics simultaneously. Most importantly, the TEPS theory offers a lens to gain an understanding of peer production that transcends the silos of either technological or economic viewpoints by integrating them, meaning the theory is therefore more comprehensive. In addition, existing literature proves the legitimacy of this method, such as Kostakis and Bauwens (2014) or Pazaitis et al. (2017), who view the diffusion of peer production through the lens of TEPS theory. Furthermore, TEPS theory was developed from an analysis of historic techno-economic paradigm shifts which shed light on patterns that such transformations are subject to. These patterns and conclusions drawn from these historic shifts are particularly insightful for approaching RQ4. The TEPS theory is explored extensively in chapter 3.1, which is followed by chapter 3.2 which applies the theory to the ICT paradigm, the current TEP.

To give a precise understanding of what is meant by leveraging the forces of peer production for green growth, chapter 5 develops a deeper understanding of peer production. With this as a basis, OSH and its documentation are addressed, because it is the documentation where digital collaboration and in some cases peer production can have significant roles in the context of this study. Subsequently, this role is laid out precisely in chapter 5.3.

As the assumed potential of peer production for green growth has been explained, chapter 6 attempts to verify whether there is empirical evidence for the possibility that the same or similar forces of peer production in the realm of digital information production can be leveraged in the realm of hardware. Therefore, data from different projects of digital collaboration has been acquired ranging from software to hardware and successful to unsuccessful. By analysing this data with fsQCA, RQ1 can be approached (to what extent does peer production of hardware occur compared to inherently digital goods such as software). In order to do so, peer production needs to become measurable to compare different projects in terms of their degree of fit to the concept of peer production. This has not been conducted in literature before and is a unique and significant contribution from this study. Therefore, the peer production coefficient (PPC) is developed. The PPC quantifies peer production as a coefficient of the function of the distribution of contributions among peers and the total number of contributors. Thereby, a project with many contributors all contributing a lot gets a high PPC, whereas a project where most of the contributions are distributed among a small number of contributors gets a low PPC. This is elaborated on extensively in chapter 6.1.4.

In fsQCA, the Quine-McCluskey algorithm is employed to reduce a truth table, which represents all possible combinations of conditions and their associated outcomes, into a simplified set of logical rules or configurations. The algorithm is a method of Boolean algebra to minimise logical expressions by systematically finding the simplest combinations of conditions that explain an outcome. The algorithm’s function in fsQCA is to identify the essential conditions and their combinations that are sufficient for the outcome while removing redundancies. This process generates three different types of solutions: complex (all observed configurations), parsimonious (minimal configurations using logical reduction), and intermediate (in between complex and parsimonious). The algorithm ensures that the configuration solutions are consistent with the data. As mentioned, fsQCA is a methodology with both qualitative and quantitative elements. Qualitative Comparative Analysis (QCA) probes combinations of conditions that are sufficient for the occurrence of an outcome (see Ragin, 2000; see Rihoux & Ragin, 2009). Hereby it contrasts linear regression analysis, which calculates the net effect of variables on an outcome.

In essence, the main arguments for using fsQCA in this study are; 1) the data available is asymmetric, so linear regression is not well suited (see Pappas & Woodside, 2021), 2) the number of cases that the author has sufficient knowledge of and can access is limited, which results in a typical use case for QCA (Jordan et al., 2011), 3) the studied fields are subject to equifinality, which means that in each fsQCA, different combinations of conditions lead to the respective outcomes. With just a few conditions, one may argue that the outcome could have been achieved with simpler methods such as using the Pearson correlation coefficient. In order to obtain valid results with correlation (e.g. Pearson correlation index), the sample would have to be representative, which is not the case for this study's samples. The fact that fsQCA was used does not weaken the results, however.

The fsQCA output provides an answer to RQ1, but does not explain the causal relationship. To understand the causal relationship, the economic characteristics of the goods are analysed, whether this is digital information, which is itself the product, or hardware documentation, where the digital documentation is just an abstraction of the actual product, the hardware. Specifically, analysing the transaction and marginal costs are, in this case, fruitful parameters for analysis. For a sufficient picture of the dynamics in digital collaboration, network effects are looked at as well. Together, these tools can explain the results of the fsQCAs.

As fsQCA1 will show, digital collaboration in the development of hardware does not reach as high levels in the PPC as collaboration in the development of inherently intangible goods does. However, fsQCA2 presents the dynamic that if digital collaboration in the development of hardware is financially compensated, it tends to be more successful and comes along with higher scores in the PPC. This allows for the conclusion that global pooling of resources in the production of hardware documentation has a significant potential for ecodesign and therefore green growth. Yet to realise this potential, certain infrastructure that facilitates financial compensation in a decentralised way is required.

To develop an outline of such infrastructure, it is necessary to first clarify what a suitable economic governance arrangement along a value chain of an economy that leverages peer production for green growth would be (RQ2). Here again, transaction and marginal cost analysis are applied. The transaction cost methodology was first brought up by Ronald Coase in his 1937 article "The Nature of the Firm", where he defined transaction costs as those costs that arise in addition to the price of a product. Typical transaction costs are policing and enforcement costs, bargaining costs or search and information costs. Coase derived the size of firms that organise production as a function of its transaction cost. The higher the transaction cost, the larger the size of the firms.

Adapting Coase (1937), Benkler (2002) argues that the rise of the internet has decreased transaction cost of information production in some branches and that this is where peer production has emerged. In this context, peer production is when the smallest unit of economic actors, i.e. individual people (peers), produce in mutual coordination. Similarly to Benkler (2002), the author wants to analyse the effect that a software infrastructure like Fab City OS would have on distributed production in the aforementioned Fab City sense of the term.

The transactions of a green growth economy that leverages forces of peer production (GGEPP) differ significantly at different stages of its value chain. Adapting von Hippel's (2005) differentiation between design and production due to the diffusion of 3D printing, this study differentiates a GGEPP into three phases of its value chain, because in the beginning of each phase a significant change in transaction and or marginal costs occurs:

1. Inventing and designing OSH products,
2. Global Digital Commons - Global Digital Federated Network,

3a. Regional E-Commerce: Marketing and Sales,

3b. Replication of physical object (manufacturing), after-manufacturing (use, update, upgrade, repair, adaption) and separation into modules or homogenous material stacks for material recovery.

To answer RQ2, the distinguished phases are analysed with an adaptation of Benkler's (2002) methodology. This will enable to predict where which type of economic governance would emerge with an infrastructure such as Fab City OS: market, firms or peer production.

It is assumed that in the long run, peer production would prevail in the global digital realm and markets and firms would prevail in the local, physical realm. This is because at the local level, which deals with physical resources for manufacturing, repairing, adapting and recycling, processes cannot be optimised, digitalised and automated so much that the transaction cost would be sufficiently low for peer production to emerge. Nevertheless, the firms operating production at the local level - enabled through global digital commons - may become smaller. Therefore, products we use daily would be designed globally, and manufactured locally (see Kostakis et al., 2015a), not abroad. A marginal cost analysis of the different stages of the value chain of distributed production will support this, because moving bits at the global, digital level has low marginal costs, whereas moving atoms at the local, physical level has higher marginal costs. According to microeconomic theory, it is at the local level where profits are to be made, i.e. markets emerge, and at the global level where peer production emerges.

As developed, a significant hurdle to the realisation of the potential of a GGEPP is the larger amount of individual contributions in the digital collaboration on hardware. The larger the individual contributions are, the more the contributor relies on a participation of the economic exploitation of his contribution or its derivatives. This is a requirement that technology and regulation could solve, which is outlined in chapters 8.5 and 8.7. This is done by adopting working mechanisms from other areas and projects. More precisely, chapter 8.5 develops an outline of an exemplary digital infrastructure that would fulfil the necessary conditions for a GGEPP, as laid out in this study, to emerge. Chapter 8.6 validates the conceptual originality of the digital infrastructure. For this purpose, it conducts a literature review in SCOPUS and Web of Science.

As a potential vision for how a GGEPP could operate has been laid out, chapter 8.7 uses the TEPS framework to develop a transformation path towards realising such a vision (RQ4). In line with the Perezian framework, subchapter 8.4 lays out two trajectories for how a GGEPP could evolve. Hereby, the work of Kostakis and Bauwens (2014) is used as a method and applied to this context. As Perez suggests, finance needs to be guided to push the new mode of production into wide diffusion. Accordingly, chapters 7 and 8.7 lay out how finance could be guided to push leverage forces of peer production for ecodesign. Subsequently, chapter 8.7 is subsumed into a broader policy approach. At last, chapter 9 makes this research's limitations transparent and gives an outlook for future research in this context. Ultimately, chapter 10 concludes the findings of this study.

To conclude the methodology section, the elaborated research design is reflected in terms of its validity. In evaluating the research design, both internal and external validity play a crucial role. Internal validity refers to the extent to which the research accurately identifies causal relationships within the studied phenomena. In this study, internal validity is supported through methodological triangulation: the combination of qualitative reasoning, fsQCA, and literature reviews ensures that insights are not drawn from a singular perspective. The development and application of the Peer Production Coefficient (PPC) as a novel operationalisation of peer production further increases internal validity, as it introduces a transparent and consistent metric that allows for comparing different cases. The validity of causal configurations identified through fsQCA is ensured through careful case selection and a clear definition of conditions and outcomes based on theoretical grounding, particularly from transaction cost economics and the TEPS framework.

External validity, or the generalisability of findings, is addressed more cautiously. Given the exploratory and qualitative nature of much of this study, its findings are not intended to be statistically generalisable. Rather, the use of fsQCA allows for analytical generalisation: identifying patterns that may recur under similar configurations of conditions. The heterogeneity of the examined cases (ranging from successful to unsuccessful, software to hardware) enhances the scope of transferability by illustrating peer production in varied contexts. Still, generalisation beyond the cases under study requires careful interpretation, especially because the specific conditions enabling leveraging peer production for green growth may be shaped by context-dependent technological, economic, or infrastructural factors.

The research process is primarily inductive, though it contains deductive elements. The inductive aspect is most evident in the empirical exploration of peer production across diverse projects and the development of the PPC as a new analytical tool. Insights emerge from empirical observation, which then inform theory-building and conceptual development. However, this inductive approach is framed and supported by a deductive layer: theoretical lenses such as transaction cost economics and the TEPS framework guide the selection of relevant variables, help shape the research questions, and provide a scaffold for interpreting empirical findings. This combination reflects the iterative nature of the research process, in which theory and data inform each other throughout the study.

From an epistemological standpoint, this study is rooted in critical realism. It acknowledges the existence of real structures and mechanisms, such as economic governance regimes and technology, that shape observed phenomena. However, it also recognises that our knowledge of these structures is mediated through interpretation and therefore fallible. This is reflected in the use of both empirical data (e.g., fsQCA) and theory-informed reasoning (e.g., transaction cost economics, TEPS) to make sense of complex socio-technical systems. By combining empirical evidence with a strong theoretical framework, this study aims to uncover plausible mechanisms behind observed outcomes, rather than merely describing surface-level correlations.
Ontologically, this study is grounded in a worldview that acknowledges the created order as

designed and purposeful, reflecting a Tanakh-based understanding of reality and the Jewish roots of the author. Following this worldview, the world is not a random or chaotic system but a creation imbued with meaning, design, and order by a sovereign Creator. Here, human beings, as image-bearers of God, are endowed with creativity, reason and moral responsibility which underlie their capacity for creation, collaboration, and stewardship over God's and their' creation, i.e. what they produce. Peer production has a potential to give individuals freedom from economic and technologic coercion. Viewed in this light, the value of peer production is not merely economic or technological in itself, but a derivation of its pro-human potential to enable individuals to create, i.e. fabricate, as a reflection of the creating God. Moreover, this ontology affirms that human agency operates within a moral and spiritual framework, which should aim toward justice, sustainability of God's and their' creation, and the common good, principles that resonate with the call to stewardship found throughout Scripture (e.g., Genesis 1:28, Micah 6:8). As such, the analysis of and activism for a pro-human production model in this study is ultimately framed within a broader vision of responsible participation in creation.

3. Theoretical Framework

This study derives a suitable economic governance arrangement of a GGEPP value chain and the contours of a specific technology as an infrastructure that would be necessary for such an economic governance to realise itself upon. To structure and guide this process of research, Carlota Perez's theory of TEPS (Perez, 2002, 2009 & 2010) is chosen as the theoretical framework. This theory offers an analytical tool for understanding interwoven economic, technologic and societal transformations and how their directionality can be steered, to a certain extent, towards a common good. The framework can also be used to identify the enabling and constraining factors that influence whether a mode of production becomes dominant. The TEPS can be positioned in the field of evolutionary and institutional economics, but it can offer vital insights for other fields such as business administration or policy making. Chapter 3.1 first lays out the TEPS theory in general, whereas chapter 3.2 applies it to the context of this study.

3.1 The Perezian Theory of Techno-Economic Paradigm Shifts as the Analytical Framework for this Study

Before applying it to a GGEPP, this subchapter introduces the TEPS theory. The TEPS theory originates from the Schumpeterian school of thought, which states that technological and economic developments are interrelated. This reflects itself in its distinction between inventions and innovation. Innovation is of economic nature but relies on technological inventions and inventions typically diffuse when companies make a product out of it. This diffusion of innovation has a distinguishable direction and pace. While usually starting slow, it gradually becomes faster and fades out with a slower pace again. Directionality means the actual path taken within the space of possibilities depending on what is tacitly perceived as an improvement of a technology or service. Perez (1985) adds that the described dynamics do not only apply at the individual technology (microlevel) but also with larger groups of technologies (meso level) which she names TEPs.

TEPs are initiated by an important technological breakthrough like Intel's microprocessor which started the information revolution. The technological progress is accompanied by products and infrastructures that utilise and spread each other with self-enforcing feedback loops (Perez, 2002, 2010). One of Perez's key insights is that it is not only a new technology that spreads, it also changes what is done in the economy and society and it also shapes how it is done. A TEPS has a profound impact on how business is conducted, which infrastructure is needed and how production is organised, which Perez subsumes as each TEP's 'common sense'. There are typically multiple new infrastructures that change transportation networks. This radically decreases the costs by benefitting the reach, speed and reliability of products, people, energy and information.

Starting from the initial industrial revolution in England (1770s), Perez identifies five TEPs (see table 1 below). This subchapter emphasises infrastructure more than Perez does in her elaborations, because infrastructure is needed for the further argumentation of this study as what it develops later on can largely be understood as an infrastructure in the Perezian sense.

	Techno-economic 'common sense' innovation principles	New or redefined infrastructures
TEP 1: The Industrial Revolution 1771-1828	Factory Production Mechanisation Productivity: time keeping and saving Fluidity of movement (as ideal for machines with water power and for transport through canals and other waterways) Local networks	Canals and waterways Turnpike roads Water power (highly improved wheels)
TEP 2: Age of Steam and Railways 1829-1874	Economies of agglomeration/Industrial cities/National markets Power centres with national networks Scale as progress Standard parts: machine-made machines Energy where needed (steam) Interdependent movement (of machines and of means of transport)	Railways (use of steam engine) Universal postal service Telegraph (mainly nationally along railway lines) Great ports, great depots and worldwide sailing ships City gas
TEP 3: Age of Steel, Electricity and Heavy Engineering 1875-1907	Giant structures (steel) Economies of scale and plant/ vertical integration Distributed power for industry (electricity) Science as a productive force Worldwide networks and empires (including cartels) Universal standardisation Cost accounting for control and efficiency Great scale for world market power/ 'small' is successful, if local	Worldwide shipping in rapid steel steamships (use of Suez Canal) Transcontinental railways (use of cheap steel rails and bolts in standard sizes) Great bridges and tunnels Worldwide telegraph Telephone (mainly nationally) Electrical networks (for illumination and industrial use)
TEP 4: Age of Oil, the Automobile and Mass Production 1908-1970	Mass production/mass markets Economies of scale (product and market volume)/horizontal integration Standardisation of products Energy intensity (oil based) Synthetic materials Functional specialisation/hierarchical pyramids Centralisation: metropolitan centres-suburbanisation National powers, world agreements	Networks of roads, highways, ports and airports Networks of oil ducts Universal electricity (industry and home) Worldwide analogue telecommunications (telephone, telex and cablegram) wire and wireless

	and confrontations	
TEP 5: Age of Information and Telecommu-nications 1971 - today	Information-intensity (microelectron-ics-based ICT) Decentralised integration/network structures Knowledge as capital/intangible value added Heterogeneity, diversity, adaptability Segmentation of markets/prolifera-tion of niches Economies of scope and specialisa-tion combined with scale Globalisation/interaction between the global and the local Inward and outward coopera-tion/clusters Instant contact and action/instant global communications	World digital telecommunications (cable, fibre optics, radio and satel-lite) Internet/electronic mail and other e-services Multiple source, flexible use, electric-ity networks High-speed physical transport links (by land, air and water)

Table 1: Five TEPs with a new 'common sense' and infrastructure

Source: based on Perez (2002)

Furthermore, according to Perez (2010), there are three areas of practice and perception within which TEPs manifest at the same time:

1) In the dynamics of the relative cost structure. The new TEP requires a relatively cheap input resource, which makes the new mode of production more lucrative than the old. These were, for example coal, then oil in the fourth and microprocessors in the fifth TEP. The increasing usage of the new infrastructures decreases cost per unit which speeds up the diffusion of the new TEP.
2) In the perceived spaces for innovation.
3) In the organisational criteria and principles (see the second column 'common sense' of the table above).

The TEPS theory divides each TEP into an installation and a deployment period with a turning point in between. The turning point is usually when a financial crash occurs which leads to a wider economic crisis. It is investment for speculative gains of companies of the new technologies that lead to overvaluation, meaning financial bubbles. From then onwards, it is possible for either a so-called golden age, where the forces of the current paradigm are balanced and harmonised by synergising policy, or a gilded age, where there is no socio-economic uplift of larger parts of society, to manifest. A main vehicle of policies aiming for transforming into a golden age is to make financial capital invest in real production instead of speculation.

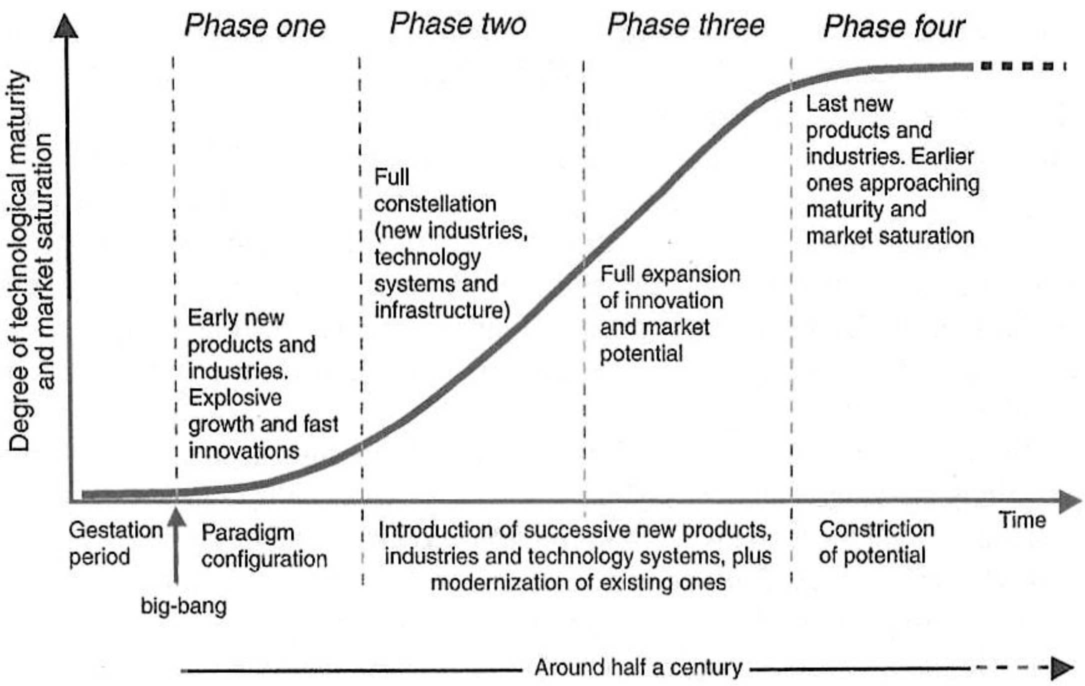

Figure 1: The life cycle of a technological revolution

Source: Extracted from Perez (2002, p. 30)

3.2 The Current Techno-Economic Paradigm Shift

According to Perez (2002, p. 11), the fifth TEP is the Age of Information and Telecommunications (ICT paradigm). The big bang that initiated this revolution occurred when Intel announced its microprocessor in Santa Clara, California in 1971.

Perez (2010 & 2015) elaborates on the ICT paradigm that, as listed in table 1 in the previous chapter, the main infrastructures are world digital communications (cable, fibre optics, radio and satellite), especially full internet access at low cost. The main new input resources that make the paradigm possible are cheap microprocessors and cheap universal information and communication technologies. The perceived spaces for innovation are digitalisation, turning products into services and reducing materials and energy consumption. This could massively up the share of services and intangible goods in overall production and in lifestyle. In sum, this path opens up the possibility of decoupling economic growth from resource extraction, i.e. green growth. The main organisational criteria and principles are decentralisation, virtualisation and seamless interplay between the global and the local.

The ICT paradigm had a first crash when the dot.com bubble burst in the early 2000s and a second crash in the late 2000s, with the bankruptcy of Lehman Brothers. Following the crash, more than half a century after the invention of the microprocessor, the ICT paradigm should already have reached its maturity phase. It is clear that the directionality for a golden age of the ICT paradigm should be sustainable[4] growth. As of 2015, the ICT paradigm has not drastically reduced material consumption that had been heavily increased by the previous "American Dream" paradigm. So, the maturity of the ICT paradigm has not yet been achieved. On the contrary, massive distribution of ICT has rather caused rising energy and materials consumption, says Perez (2015).

A golden age for the ICT paradigm would see markets engaging broadly in green innovation that is enabled by ICT. For this to happen though, Perez (2015) continues to argue that finance would have to support this by investing in the production of such green technology, infrastructure and products, rather than in speculation. Otherwise, green markets will stay too small and investments in the market will remain too risky to reach a sufficient size. It is a sophisticated policy's role to make financial capital invest in production in the directionality of green growth, leveraging the potential force of ICT. The task is to shape the conditions for finance to invest in the production economy and not in internally oriented speculation. Such policies must be

[4] Within the TEPS theory, "sustainable" is to be understood as emphasising its ecological side. Social and economic sustainability are inherent to the theory's definition of a golden age.

bipartisan, long term and credible. In other words, policy should tilt the playing field to get an effect like suburbanisation in the golden age after WWII (Perez, 2015).

Perez (2015, pp. 212–213) outlines several concrete policies to foster a "golden age" of the ICT paradigm:

1. Shift the tax burden from labour to energy and materials: Perez advocates for a tax system that leverages digital databases to tax "bads" rather than "goods”. For instance, taxing resource and energy consumption instead of labour and traditional consumption would promote resource efficiency, energy conservation, and greater employment. Additionally, this approach would stimulate consumer spending on intangible goods and services.

2. Promote durability and maintenance: By holding producers accountable for the full life cycle of their products, this policy would encourage sustainable practices, such as manufacturing for durability and fostering a circular economy. It would also support the growth of rental and maintenance-based business models.

3. Redefine wealth metrics: Perez emphasises the need to move beyond GDP, which she views as a limited and often distorting measure in the knowledge economy. New metrics should better reflect energy and material use while capturing diverse forms of value creation and well-being enhancement.

4. Encourage sharing and collaborative economies: ICT has enabled innovative, network-based sharing systems, from time exchanges to collaborative creative projects. By facilitating such models, this approach can drive the transition to a green economy focused on sustainability, services, and personal well-being.

5. Reorient financial systems: Rather than imposing controls, Perez proposes taxing

short-term financial gains at higher rates, with lower rates for long-term investments. This would incentivise investments in the real economy and promote long-term projects. Additionally, public funding for green research, market creation, and infrastructure redevelopment is essential for fostering risky but vital innovations in sustainable directions.

The European Green Deal matches Perez's prescribed policies to a large extent. Chapter 4 will take this up and explain further.

Comparing the ICT paradigm with previous paradigms in terms of their time spans, the question arises as to why the ICT paradigm takes longer to deploy. This study argues that the reason for this delay can be understood when comparing the microeconomic characteristics of the ICT paradigm and previous TEPs. Before giving this explanation, this chapter highlights some arguments about the ICT paradigm's maturity in the context of the TEPS theory.

Perez (2013, 2015) herself states that the delay is due to a lack of proactive state action. Later, Perez (2022) lists several factors which explain why the ICT paradigm takes longer to deploy:

- This paradigm mechanises mental labour, which is different from other paradigms where physical labour was mechanised.
- This paradigm is global, which is why the process of change of supply and demand is more complex. For example, the entrance of China and countries from the former USSR into the global market alone with large numbers of low-wage workers have led to a prolongation of the mass production paradigm.
- The internet as the infrastructure for information was only available 23 years after the invention of the microprocessor.
- Decoupling of finance from production slows the transformation process down, because in previous paradigms, finance's support for new production methods spurred the new paradigm to develop.

Another explanation for the delay is the deep transitions theory by Schot & Kanger (2018). According to their theory, a TEPS occurs in rhythms they describe as deep transitions. As the first deep transition is now being overtaken by the second, it is natural that also this TEPS takes longer.

This study adds a third perspective onto the subject, a microeconomic one. From a microeconomics perspective, prices are optimal when they equal marginal cost of production. Moving atoms has a higher marginal cost then moving bits. Taken to the extreme, profits are to be made by moving atoms, while moving bits should be nearly free. Hence, there is much economic potential for OS software and other products for which a perfect copy can be digitised, such as text. This is not so for OSH, where its digital documentation is always just an imperfect abstraction of the actual physical good. This claim is to be taken carefully because software always requires maintenance. So, while software is also not close to zero marginal costs, these costs are much lower than moving atoms. It helps to also consider transaction costs to get a better understanding of the economic implications of the deployment of OS soft- and hardware in production. This synthesis is conducted later in this study. For now, when arguing why the ICT paradigm is taking longer to mature as a TEP, it is sufficient to solely look at marginal cost. The argument is that due to the ICT paradigm, especially when taken into a sustainable growth direction, is largely virtual and therefore a fundamentally different premise for conducting business overall. Business administration is premised on scarcity of resources. If the main input resource, information, is not scarce but abundant, it is logical that the way businesses operate changes. Chapter 8 outlines how such an economy would look. In a golden age of the ICT paradigm, what is digital is produced globally, whereas everything physical is produced locally. That is a more fundamental change compared to previous TEPSs and therefore takes more time to deploy. The arguments approached here are explained in more detail later in this study. In a similar vein to Schot & Kanger (2018) and Perez (2013, 2015, 2022), this study argues that the ICT paradigm's TEPS is more fundamental, especially for the way businesses operate in general, and therefore takes more time to deploy.

4. Selected Aspects in the Context of the European Green Deal

Almost all (more than 90%) of biodiversity loss and water stress and around half of total greenhouse gas emissions are due to resource extraction and processing (European Commission, 2020). Hence, a circular economy (CE) is an effective approach to improve biodiversity and water metabolism and reduce greenhouse gas emissions. This chapter starts by introducing the general idea of a CE and how it compares with GGEPP, as the ESPR references it. Following up, this chapter elaborates the ESPR and the DPPs of the ESPR as well as DPPs in general. At last, the ESPR's approach to enforce ecodesign is discussed critically.

4.1 Brief Introduction to Circular Economy and its Congruence with the GGEPP

The concept of a CE has gained significant traction in recent years as a response to the pressing challenges of climate change, resource depletion, and waste generation. It emphasises the reuse, repair, and recycling of materials and products, standing in stark contrast to the traditional linear economy, characterised by a "take-make-dispose" model. In other words, the CE is about closing material flows. However, it needs to be emphasised that GGEPP and CE are not identical. One could say that the GGEPP is one type of a CE, as it is the goal of the GGEPP to close material flows on the local level as well. But GGEPP's rationale of leveraging peer production in the development phase to boost transitioning towards a CE is not what is typically meant by CE in literature, especially when focusing on the collaborative development of physical products. Jäger-Roschko & Petersen's (2022) review revealed that CE research in the context of information sharing focuses on subsequent phases of the value chain, not the development phase. However, it is crucial to focus on the development phase, because here it is decided how open information will be shared.

To fully understand the implications and potential of the CE, it is essential to consider it within the broader context of technological and economic transformations. As described in chapter 3, within the TEPS framework, the CE, especially a GGEPP, can be seen as a substantial concept for attaining a golden age of the ICT paradigm, where economic growth is increasingly virtualised and decoupled from resource extraction.

4.2 Description of the Legislation

A major critical aspect in transitioning towards a CE is ecodesign. Ecodesign describes products that are durable, repairable, updateable, recyclable, modular, energy-efficient, and able to be disassembled and put to further use while having a low carbon footprint along their life cycles. Hence, it is a crucial question how product developers can be moved to design ecologically. The ESPR addresses this specifically. It is one of the core elements of the European Green Deal. It is supplemented by the Directive on Empowering Consumers in the Green Transition, that provides consumers with information on the longevity and repairability when purchasing. In addition, the Directive on repair of goods enforces repairing of many physical products.

Before laying out the legislation in more detail, it is worth taking a look into a historic comparison with the American New Deal in the 1930s. The United States' New Deal, implemented in response to the Great Depression, sought to revive the economy through massive public works, financial reforms, and job creation. It was a paradigm shift that not only aimed to restore economic stability but also aimed to redefine the relationship between government and the economy. Similarly, the European Green Deal, e.g. through the ESPR and the two directives named above, aims to reshape the economic landscape by addressing the existential threats of climate change and resource depletion. Both initiatives represent significant government intervention to catalyse change in response to pressing societal challenges.

The **ESPR** sets a framework for the establishment of ecodesign requirements. All physical products, with a few exemptions such as vehicles, food, feed and medical products, have to fulfil these requirements in order to be sold on the EU market. It also establishes a DPP, unfolds a framework that prohibits the destruction of unsold goods and regulates green public procurement. The legislation is will be rolled out successively through DAs from the EU Commission per product branch. The first branches are clothes and apparel as well as batteries. Economic operators are given at least 18 months to comply with the requirements outlined in each DA. The ESPR establishes the following parameters ("product aspects") to assess the desired impact of ecodesign requirements:

- Durability
- Reliability
- Reusability
- Upgradeability
- Repairability
- The possibility of maintenance and refurbishment
- The presence of substances of concern
- Energy use and resource efficiency
- Recycled content
- The possibility of remanufacturing
- Recyclability
- The possibility to recover the materials
- Environmental impacts, including carbon footprint and environmental footprint
- Expected generation of waste

DA on textiles are planned to be enacted at end of 2025, companies will then have 18 months to comply. Business are impacted already as of 2025/26.

The DA can enforce economic actors (EAs) that:

- Are upchain to cooperate in order to verify information in the context of ecodesign
- Disclose the quantity of goods subject to the DA to the EU Commission
- Have their goods automatically measure the energy they consume or other ecodesign parameters
- DPPs contain info on repair

The ESPR introduces a DPP that manufacturers are obliged to provide for all products that are subject to the ESPR's DA. A DPP is a file that contains information about a physical product and can be assessed by customers as well as other stakeholders along the value chain. The DPP is usually accessed by scanning a unique identifier on the product itself or by clicking on a link in an online store. Subchapter 4.4 gives more details on DPPs. The following lists what the ESPR sets out for its DPP specifically:

- DPPs must be fully interoperable with other DPPs required by the ESPR
- All relevant actors such as consumers and manufacturers must have easy access to the DPP, free of charge
- A unique identifier connected with data carrier must be provided on the product, its packaging or on documentation that comes with the product
- Data must be based on open standards, in interoperable format, and when appropriate machine-readable, searchable and transferable through an open interoperable data exchange network without vendor lock-in
- EAs must provide dealers and providers of online marketplaces with a digital copy of the unique identifier
- DPPs can be stored either by EAs responsible for their creation or by DPP providers

As part of the ESPR's information requirements, EAs will transparently display, for example on the DPP, how a good is classified in classes set by the EU, in terms of ecodesign performance. So, customers will be able to assess which product performs best in terms of ecodesign. The main information source is the DPP, but in some cases the information can be on the product itself, on the product's packaging, on a label, in a user manual, or on a free access website or application.

Next, the **Directive on repair of goods** is briefly described. The overall aim of the directive is to increase the longevity of a selected range of products:

- Manufacturers are obliged to repair their products outside the liability of the seller until it is no longer possible. They must do so at a reasonable price.
- Products include electronic displays, dishwashers, washer-dryers, washing machines, vacuum cleaners, servers and data storage products, mobile phones, tablets and small portable batteries. This list is extended over time.
- A European online platform for repair is established that enables consumers to find repairers, sellers of refurbished goods, purchasers of defective goods for refurbishment or community-led repair initiatives.
- The repairability and reusage in the after-sales phase outside the liability of the seller is addressed.
- The manufacturer can subcontract the repair and must not perform the repair himself or herself.
- If the manufacturer resides outside the EU, the representative in EU, importer, or distributor are responsible.
- Contractual clauses, hardware or software techniques that impede repair are prohibited.
- The manufacturer cannot refuse repair when another repairer has repaired a good before.
- Manufacturers must allow usage of spare parts from sources other than themselves.
- There must be general improvement of service of repair of goods.
- Product repair must be affordable.
- Repair regulation across member states must be unified

- Manufacturers must provide prices of typical repair on a free-to-access website
- A standardised European Repair Information Form must be established, which shall allow consumers to better assess and compare different repair services. The form includes information that will influence consumer decisions such as naming which part of the good is broken, the cost of the repair, how long the repair will take and, if offered, how much the transportation will cost. The form is optional.
- Spare parts manufacturers must set reasonable prices that do not deter repair.

The directive’s timeline is that it has been adopted on the 13th June 2024. Member states have to form the directive into national law and apply it from the 31th June 2026.

As the third element of legislation, the **Directive on Empowering Consumers in the Green Transition** is explored further. The directive attempts to ensure that consumers have the information they need to make sustainable consumption decisions, for example, information about the circularity performance of goods. It hereby aims at making sure that such information is reliable.

- Fight unfair green product labelling or “greenwashing”
- Fight planned obsolescence
- Prohibit software updates that decrease the good’s performance
- Before purchasing, consumers must receive information regarding repair services

The directive will be enforced from the 27th March 2026.

Altogether, the outlined legislation poses a substantial push towards implementing ecodesign on the EU market. Many manufacturers are confronted with this major reform, which forces them to change. The rationale and working mechanism behind the legislation is described and analysed in the following subchapter.

4.3 Description and Analysis of Working Mechanism of how ESPR is to Achieve Ecodesign - Frictions in a Green Transition which is Enforced by Raising The Standards

The way the EU approaches pushing for the transition towards a CE is twofold. On the one hand, the EU successively raises the ecodesign requirements and other standards. On the other hand, it enforces manufacturers to make transparent how green a product really is and thereby creates a level playing field for competition in this aspect. The former approach is definitely a very effective measure to raise the standard in terms of the parameters for ecodesign laid out in the ESPR. However, a transition that is forced upon businesses causes more friction compared to a transition that is performed from businesses' self-interest.

To establish a working mechanism of green transition where businesses transition due to their own interest instead of being forced to do so, the two approaches identified above could be supplemented by another measure in the future. The EU Emissions Trading System can give an insightful example. It follows the principle of cap and trade where the overall emission is capped and emitters can trade the right to emit. Thereby, emitters have a financial incentive to reduce emissions. Something similar in the realm of transitioning towards a CE becomes more possible due to the ESPR because it also requires manufacturers to report, for example, how much unsold products they destroy. Based on that number, the total amount could be capped and traded. The cap-and-trade principle is more dynamic and could be a viable supplement to existing legislation. The cap-and-trade principle is just one way to support a transition with less friction. Chapter 8.5 elaborates on an alternative which is well suited for the conditions at hand.

4.4 Digital Product Passports

A DPP in the context of a circular economy is a tool that provides comprehensive, accessible information about a product's life cycle, including its materials, components, manufacturing processes, and recycling or disposal methods. It can contain or link to all kinds of data, and is also a repository of files necessary for manufacturing such as CAD and CAM files or bills of materials. DPPs are seen as a key technology for transitioning towards a CE (Adisorn et al., 2021). This digital record enables consumers, manufacturers, and recyclers to understand a product's sustainability attributes, promoting transparency and facilitating responsible consumption. By allowing stakeholders to track and assess the environmental impact and potential for reuse or recycling, the DPP supports the principles of the circular economy, encouraging the design of products that are easier to repair, recycle, and repurpose, ultimately reducing waste and enhancing resource efficiency.

The DPP concept has emerged as a promising solution to address the growing complexities of product life cycles and the increasing demand for sustainability and transparency. Building upon the foundations laid by earlier technologies such as barcodes and RFID tags, DPPs offer a comprehensive and interconnected approach to tracking and managing products throughout their entire circular economy value chain. Furthermore, the integration of IoT sensors into products can provide real-time data on product usage, condition, and location. This information can be used to optimise maintenance, identify potential defects, and facilitate efficient recycling and reuse.

This study differentiates between design and material passports. The former tracks events that happen in the virtual realm of a product's value chain[5] and the latter tracks manufacturing and the after-manufacturing events where the product has materialised. Conventionally, DPPs are created in the context of raw material generation or extraction. The ESPR, as mentioned before, also adheres to this understanding which reflects a value chain where the product is developed in a central manner. In contrast, this study aims at obtaining a value chain where the product development process is also decentralised and tracked in design passports, for which the mass introduction of DPPs is a crucial enabler.

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[5] Chapter 8 elaborates on the circular economy value chain used in this study.

Interoperability of different DPP software solutions is, as mentioned in the previous subchapter, required by the ESPR and is essential for decentral logistics of a circular economy. It is a crucial enabler for the prevention of CE silos, where manufacturers only recycle materials that have been recovered from their own products. Manufacturers would be motivated to keep manufacturing centralised and distant from where the consumption occurs. Since the ESPR requires interoperability between different DPPs, it becomes more viable to recycle materials regardless of their origins.

Regarding the implementation of DPPs, it is clear that not every manufacturer is able to develop a DPP by himself or herself. Instead, there is a growing number of DPP providers that develop increasingly mature, out-of-the-box solutions. This new market of DPP providers' services is dynamic and DPP providers are mostly young companies. Apart from regulatory compliance, companies will look for secured long term operation. Arianee SAS (Société par actions simplifiée - simplified joint-stock company incorporated in France) for example, is a Paris-based startup that aims to leverage the OS Arianee protocol. Among the brands that have partnered with Arianee SAS to build DPPs are Moncler and Breitling. The fact that the Arianee protocol is OS is of high value because it builds trust. Moncler and Breitling are given agency over Arianee through their Arianee Association membership, which makes sure that the technology will always be controlled, developed and improved in the interest of its users. Other DPP providers have chosen to offer proprietary solutions.

All in all, the ESPR's mass implementation of DPPs is a milestone in utilising the potential of the ICT paradigm for sustainability. It opens up information about products to some degree, that at least enables enhanced after-manufacturing processes, ranging from repairing, upgrading, updating, separation into modules, reselling and recycling to materials recovery. What this study will continue to highlight however, is that this is a crucial precondition for the opening upchain from manufacturing, because it lowers the threshold of economic actors to engage with the product at all stages of the value chain, including its development. Altogether, the

ESPR paves the way for realising a GGEPP, as the following chapters will explain.

5. Peer Production

According to the TEPS framework, paradigm shifts can change the ‘common sense’ or structural patterns of production, as was outlined in chapter 3. This chapter introduces the idea that in the ICT paradigm, peer production can be part of that new ‘common sense’. Subchapter 5.1 starts with explaining different approaches to defining peer production. Here, how the forces of peer production can be witnessed in OS software and other digital information production will be explained. Chapter 5.2 ‘peer production and governance’ elaborates how different forms of peer production can be differentiated by, for example, the ownership structure of its backend infrastructure. In addition, the subchapter introduces the concept of transaction cost economics to differentiate peer production as one of three different types of economic governance regimes. Thereupon, subchapter 5.3 ‘peer production of hardware and its documentation’ develops how the concept of peer production has evolved from its original definition in academic literature to the claim that peer production is also applicable in the hardware realm. The difference in peer production’s applicability between the production of intangible and tangible goods is analysed by applying the original transaction cost-based derivation for when peer production occurs in the production of intangible goods to the context of hardware.

5.1 Defining Peer Production

Increasing diffusion of access to the internet across the globe means that geographically dispersed people (i.e. peers) have become able to exchange digitised information at low cost. This has given rise to a phenomenon where large numbers of peers collaborate in the production of value, which can be social interaction, knowledge in the form of text or code. Individual contributions are often small and voluntary but because of the large numbers of contributors a lot of value is being produced in sum. The first and most influential elaboration of this new mode of value production was conducted by Benkler (2002), who described it as peer production (Dafermos, 2020).

Benkler (2002) did not give a concise definition of peer production and in peer production literature its definition varies. The variation of whether or not all peer production is commons-based or commons-oriented is relevant to this study. For example, Benkler (2006) uses the terms peer production and commons-based peer production interchangeably. Another exemplary definition of peer production being inherently commons-oriented is provided by Siefkes (2010):

"Voluntary cooperation between equally entitled ('peers') who contribute to a common goal". ("Freiwillige Kooperation zwischen Gleichberechtigten ('Peers'), die zu einem gemeinsamen Ziel beitragen.")

Bauwens (2009) defines peer production as inherently commons-based and commons-oriented, but in Kostakis & Bauwens (2014) it is insinuated that how Facebook users generate social value among themselves is a form of peer production, even though the digital infrastructure of Facebook is not commons-oriented and the exchange value generated goes to the central owners of the infrastructure instead of the user, without the users having governance. Similarly, in the understanding of peer production in this study, there is peer production that is neither based on commons nor produces commons, which this subchapter returns to in the section about the governance of peer production.

This study's definition agrees with Siefkes' (2010) definition in so far that peer production is not a streamlined top-down endeavour. Peer production is when peers produce something, as opposed to when workers in a centrally-managed organisation do. In peer production, the peers assign their work packages themselves, whereas in a firm-based production employers typically assign work packages to their employees.

Another significant aspect in this context is the question of whether there can be such peer production where the peers are compensated for their contribution. In their 2021 article 'Grammar of peer production', Kostakis & Bauwens list characteristics of peer production, but do not offer a concise definition of it. Although, they state that peer producers can be financially compensated. So, the voluntariness of peer production only means that there is no central coordination deciding who conducts which work. A prominent example of this is when commercial companies such as Intel or Google pay their staff to contribute to the Linux Kernel. The companies use the peer produced Kernel for their commercial products but do not get direct revenue for contributing to it.

The fact that the developers do get paid for their contribution does not exclude their contributions, or the organisation they work for, from being considered as peer production. This aspect that large actors contribute to projects which are then still considered peer production needs to be addressed. If it would only be large economic actors that collaborate on a project, it would not be considered peer production, even if its product's legal regime is open for economic exploitation. Despite large economic actors' participation in the development of Linux, it is not ruled out as peer production because there is also a large quantity of small economic actors contributing to it. The continuation of this study elaborates on this more precisely, especially in subchapter 6.1.4, where the number of contributors and the distribution of the size of their contribution is weighed into a concise formula, the PPC, for measuring the degree to which a project can be considered peer production. The root for this understanding of peer production goes back to Benkler's (2002) study where he used transaction cost economics to explain peer production. The method of using transaction cost to analyse peer production will be explored later in this study.

This study defines peer production as a sub-case of digital collaboration, where peer production is typically conducted by large numbers of small economic actors, regardless of their motivation. They can be, for example, extrinsically motivated by financial incentives or intrinsically motivated by the pleasure experienced in contributing.

5.2 Peer Production and Governance

Since the turn of the millennium, peer production has grown in economic relevance. Without being aware of it, most people on earth engage in peer production every day, for example when they *spend* attention on social media, which can be seen as a form of value contribution. In this context, Kostakis & Bauwens (2014) highlight the importance of the governance of the infrastructure upon which peers create value. They make up a plot of two axes and four quadrants, where the vertical axis differentiates central and decentral and the horizontal differentiates commons- and capital-oriented forms of peer production. All points on the graph represent forms of peer production with different governance arrangements.

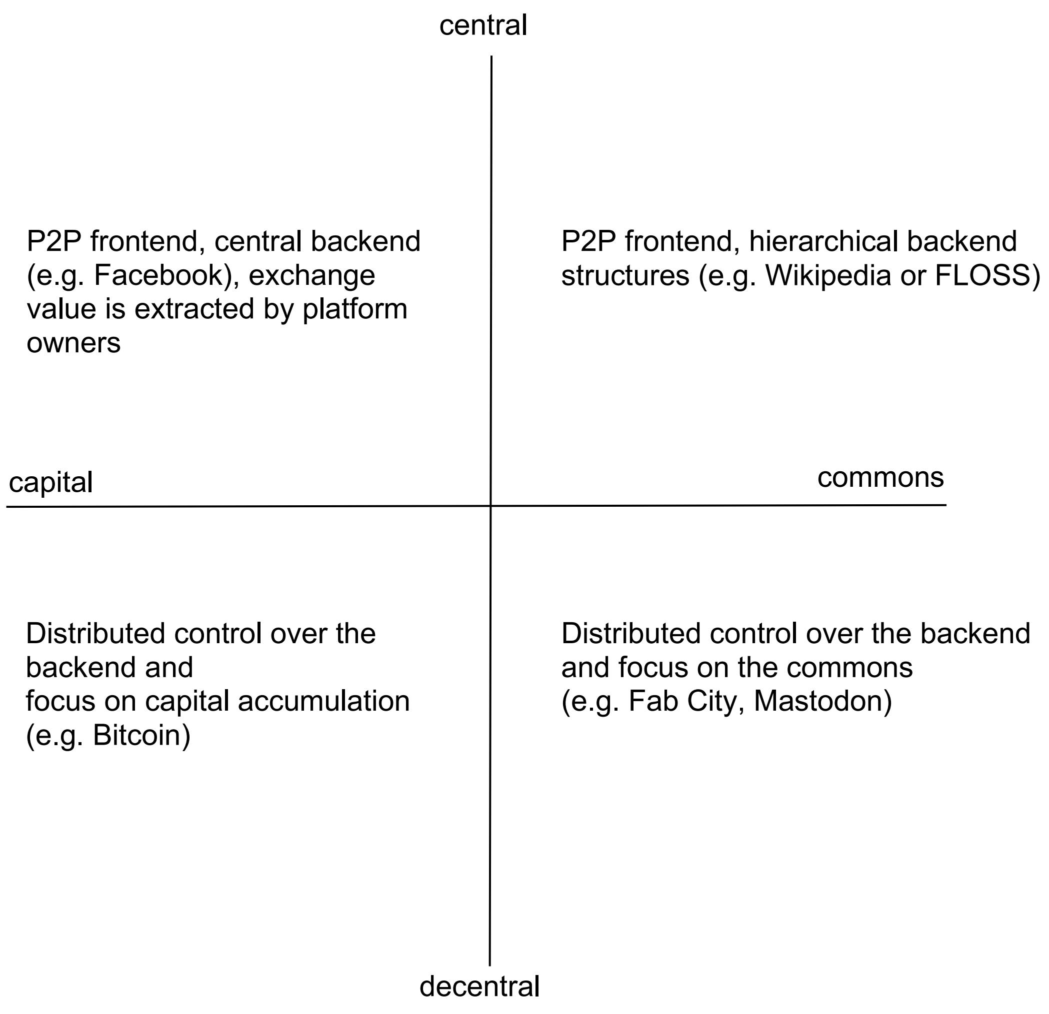

Figure 2: Two axes and four quadrants

Source: see Kostakis and Bauwens (2014)

Hence, Kostakis and Bauwens' (2014) argument is that peer production can be differentiated between being capital- or commons-oriented and central or decentral control or structure of the backend infrastructure. Essential for this study is the insight that leveraging the forces of peer production can be differentiated into four governance types.

From the TEPS theory's perspective, only those that maximise the overall socio-economic well-being or common good are preferable. When a system's value is generated by users and they do not have a say over the platform's governance or exchange value, as it is the case in Facebook, the TEPS could be used to condemn that, if a similar service of social production is possible with the backend being decentralised as is the case with services such as Mastodon. Therefore, with TEPS theory, this study argues in favour of systems like Mastodon which are decentralised in the frontend and backend. Fab City is located in that bottom-right quadrant and is therefore favoured by TEPS in the understanding of this study.

Theoretically, a system that generates revenues for its users and is decentralised in the backend could be located in this bottom-left corner as well, because commons-orientation does not exclude users from gaining exchange value in return for their contributions. Hence, the exemplary digital infrastructure 'Fab City OS' which is developed later in this study and the GGEPP would be located in that bottom-left corner.

5.2.1 Transaction Cost Approach to Defining Peer Production - Differentiating Three Economic Governance Regimes as a Function of Transaction Costs

This study defines the archetype of peer production as a mode of production where many peers make small, self-assigned contributions. This definition stands regardless of whether peers generate direct or indirect financial remuneration from their contributions. Hence, in a project where one contributor makes up for most contributions and many only contribute very little, this study tends not to apply the label of peer production but still considers it as a form of organising where firms emerge.

In literature, there is no consensus on a precise definition of transaction costs. Although, transaction costs are usually differentiated into direct and indirect transaction costs. Direct transaction costs are those that are immediate to the actual transaction such as shipping costs or a fee one pays for making use of an online platform that executes the transaction. Indirect transaction costs are rather distant to the actual transaction, among which can be information generation costs, negotiation costs or enforcement costs.

Empirical studies tend to focus on direct transaction cost and state that it is the economic value of resources used in locating trading partners and executing transactions. Others define it as the difference between the prices paid by the buyer and received by the seller. Comparative institutional analyses, largely conducted by Williamson (1975, 1985, 1996, 1998 and 2000), investigate indirect transaction costs. Another branch of research analyses transaction costs related to government regulation (see Wang, 2003).This study defines transaction costs, if not stated otherwise, as the costs that it takes for an economic actor to participate in production to the subject of this study, which is software-enabled distributed production with a global value chain, meaning specifically the GGEPP.

As explained in the methodology chapter, this study uses the transaction cost perspective to explain the occurrence of peer production. Building upon Coase (1937), Benkler (2002) defines economic governance regimes as a function of the transaction cost within the scope of economic actions and adds peer production as a third regime when the transaction costs are low:

Transaction cost	What is most efficient	Economic Governance Regime
high	Market exchange	Pure market
middle	Organising	Market with firms
low	Peer production	Peer production processes

Table 2: Deriving economic governance regime from transaction costs
Source: by the author in adaption of Benkler (2002, p. 34)

Therefore, the decisive parameter for peer production is that it is peers, i.e. small economic actors, that are able to participate in production due to the low transaction cost.

At last, Baldwin & Von Hippel (2011) further support how the understanding of the occurrence of peer production has been shaped. They state that there are not only producer innovators, but also single user innovators as well as open collaborative innovators. In the understanding of the author of this study, open collaboration is comparable with peer production. Subsequently, Baldwin & Von Hippel (2011) give explanations for the conditions under which each type of inventor is viable, specifically depending on the communication and design costs. They state that when communication costs decrease, there is a higher chance for open collaborative innovation to emerge. In a slightly more nuanced way to Baldwin & Von Hippel (2011), this study defines communication costs as only one subset of transaction costs. Nevertheless, Baldwin & Von Hippel's (2011) insights are significant for supporting this study's understanding that decreased transaction costs tend to shape conditions in favour of the engagement of smaller economic actors in the production process.

Deriving the understanding of the conditions necessary for peer production to emerge from a transaction cost perspective forms a robust base for defining peer production in a precise manner.

5.2.2 The Occurrence of Hybrid Forms of Economic Governance Regimes

In reality, production does not always occur in one pure form of the three derivative forms of economic governance regimes. Instead, hybrid forms of economic governance regimes exist. The production of the Linux Kernel can be taken as an example here. The Kernel consists of code, which is an intangible good. Therefore, transferring an exact copy to a peer attempting to engage in production only takes access to the internet and a computer. So, in this sense the transaction costs are low. As Benkler's (2002) methodology predicts, which was laid out in the previous subchapter, there are individual contributors who are not financially remunerated for doing their work and who do not contribute on behalf of a larger organisation. At the same time, many of the contributors to the Kernel are actually paid directly or indirectly for their contributory work. Often, they are employees of big tech companies, which is why from a TC perspective it is actually firms that contribute. Therefore, the economic governance regime is not purely peer production but also includes organising/firms. Deviating slightly from this study's definition of TC in chapter 5.2.1, one could argue that at least partially, the Kernel's mode of production is subject to high transaction cost, for example because the integration costs are high. Due to the complexity of the code, it can be an enormous amount of work to check a merge request. So, the hybrid form of Linux's economic governance regime is still in line with the insight from the previous subchapter that economic governance is a function of the TC, i.e. that when TCs are higher, the contributing actors tend to be larger. The takeaway from this analysis of the Linux Kernels is that there can be hybrid forms of economic governance regimes. Subchapter 6.1.4 will develop a coefficient that indicates precisely to which degree a project adheres to peer production.

In terms of distinguishing different forms of economic governance regimes, online market-places are a phenomenon worth elaborating on for further developments of this research. The following will briefly discuss types of cases such as eBay and Amazon and whether they could be considered projects of peer production, because here, large numbers of economic actors collaborate in some form. Though, it is important to differentiate whether:

1. the product is created collaboratively, or
2. the digital infrastructure is used as a marketplace.

While collaboration on a Wikipedia article can be understood as a market mechanism in the sense that supply and demand for development tasks and development capacities meet, a complete product is also collaboratively created, which is marketed later. In parallel, even in the cooperation of employees within a company or a cooperation of companies within a corporate group, cooperation is orchestrated from above, which from the perspective of Transaction Cost Governance (TC Governance) does not lead to referring to it as a market, but rather emphasises this as being subject to the economic governance regime of organising/firm.

5.3 Peer Production of Hardware and its Documentation

In this subchapter, the peer production of hardware is discussed. First, its chances of realisation are differentiated from peer production of intangible goods. Second, hardware documentation is explored further in terms of its eligibility for being peer produced.

Kostakis and Bauwens (2014) and Kostakis, Fountouklis and Drechsler (2013) insinuate the notion that a similar growth of peer production of encyclopaedia articles and software is to be expected in peer production of hardware. It is important to note, however, that in Benkler's (2002) definition of peer production, he only speaks of production of information, which is a 'non-rival' good, with information as both its main input and output. Benkler (2002, p. 405) is explicit that he makes no claims of the applicability of his observations to traditional economic goods. This emphasis on the characteristics of a good that is being produced seems to have lost appropriate recognition since Benkler (2002) originally emphasised it.

Nevertheless, there are some projects where peer production of hardware is attempted. One of the most prominent examples is the RepRap project, initiated in 2005. It utilised the end of the patent on fused deposition modelling to build a simple printer of which they published the documentation on a Wikimedia-based platform under a General Public License. Peers around the world then contributed to the documentation which improved rapidly. Today, derivatives of its design dominate the global 3D printer's market, costing up to 1000 €. Despite this success story, peer production of hardware is still far from the growth track that peer production of information experienced. To understand why this is the case, the following takes a deeper look into Benkler's initial (2002) elaboration where he stated that there are three basic factors essential for the success of peer production of information:

1. Modularity, which describes the characteristic by which a project can be divided into smaller components (modules). For being modular, it must be possible for these modules to be produced asynchronously and indecently before being assembled.

2. Fine Granularity, which refers to the size of the modules. It is measured in the time and effort that a peer must invest to produce a module.

3. Low Cost of Integration which means that the process of assembling the modules into a whole has low cost. Benkler (2002) lists two aspects that integration in peer production has. First, a sort of quality control and integrity check and second, a process of actually putting the contributed modules together.

The following applies the three factors to hardware in comparison to encyclopaedia articles, where peer production has significant impact. Concretely, a casual 3D printer (3DP) is compared to an article on Wikipedia (AW).

In terms of modularity, the AW is much more modular, because the different elements of it are less dependent on each other. Therefore, the different parts can more likely be written asynchronously. For example, a new event in a person's biographic article can be added to the existing article by anyone who has access to the internet. Even if the one new addition of the text is factually wrong or contains spelling mistakes, it does not endanger the overall functionality of the entire text. The rest of the text is still probably correct and valuable in the sense that users can still access it. In contrast, a single mistake in the design of a 3DP can impede the functionality of the 3DP, because the different parts are often dependent on each other and most of the parts are necessary to fulfil the purpose of the 3DP. Also, the different modules of a 3DP need to fit together in the end, which requires more coordination effort to acquire modularity compared to an AW.

The granularity of a 3DP is far smaller than that of an AW, which has a very high granularity. A valuable individual contribution to an AW can be as small as writing a sentence or even one number such as a birth date or the correction of a letter, which can be considered a module. The modules of a 3DP can mostly not be broken down to an equivalent size of a digit or letter, at least not in a meaningful way. The development of the 3DP nozzle or the heating bed, can and has been separated from other geographically distributed peer producers. But the development of the nozzle itself is hard to distribute into more modules, because at some point one has to manufacture a prototype of it. Also, in successful distributed 3DP projects, the depth of distribution is far less than in an AW. Many components themselves are not completely designed and manufactured by the group of producers but are market-based off the shelf solutions. So, a typical contribution to a 3DP takes more time and effort, also because the contributions to the 3DP are digital abstractions of the actual physical artefact. The more granular the modules of a 3DP get, the more peer producers need to have to a certain degree the same physical objects at their site, which is a logistical challenge. The author of this study has experienced a distributed development of a 3DP where an outdated version of an entire 3DP was sent across the Atlantic Ocean. This outdatedness was only found out after the receiving peer started working on that prototype, which meant that the work and shipment were made in vain. That caused frustration and eventually the peer dropped out of the project. Compared to this, in an AW, it is very cheap for every peer to have the most recent version and it is more feasible to have smaller modules.

The cost of integration: At least in the end of the product development process, the 3DP has to be assembled with all its sub-modules to check that it works. Assuming many modules from across the globe, this is costly and can take a lot of time, especially if customs take longer or there is a logistical crisis, as there has been in recent years. Most often, the 3DP or its sub-modules must be brought to a place which is accessible by the one who decides on a merge. So, the peers need to either ship an exact copy or the original of the 3DP being developed or the 3DP needs to be rebuilt simultaneously, in order to check whether individual contributions are of sufficient quality. Of course, it can be that minor contributions like spelling mistakes can be merged without much effort, but often enough there is much effort involved. Comparably, contributions to an AW are of low cost to integrate. This is also due to lower fragility. As mentioned above, if one fact in a text is wrong, the rest can still be valuable for users. Aside from the cheaper quality assurance, the actual "transport" of the contribution is virtual and therefore less costly in the production of the AW.

In sum, evaluated according to Benkler's (2002) factors, hardware is much less feasible for being a product of peers compared to goods which are inherently digital information like software or encyclopaedia article texts.

When peer production of hardware is discussed, it is important to note that what is actually being discussed is the peer production of the documentation of that hardware. Hardware documentation is digitised information for remanufacturing hardware. So, it entails necessary information for manufacturing a physical good. The documentation itself is digital and intangible, but it is only the imperfect abstraction of a tangible good. One may call this 'ponderous digital goods', because it is inherently connected to physical goods. So, the hardware documentation leaves a gap between the physical and the virtual. Mariscal-Melgar et al. (2023) developed a CAD-coupled documentation to update the documentation more easily when the CAD is changed. This increases efficiency in distributed collaboration, but still does not reach the efficiency level of, for example, software. Additionally, even if the documentation process becomes more efficient, the aforementioned barriers for peer production of hardware remain.

Parts of the tangible good are inherently digital though, as the firmware or text of manuals for example. The higher the share of digital components in the product, the more likely it is to be peer produced. It is also possible that the inherently digital parts of the goods are peer produced whereas the more ponderous parts are not, which is a possibility explored later on in this study.

6. Dynamics of the Occurrence of Peer Production in Digital Collaboration in the Development of Hardware

Chapter 6 expatiates the dynamics of the occurrence of peer production in digital collaboration in the development of hardware. This is done with fsQCA, a literature review and an analysis of its economic characteristics.

6.1 Fuzzy-Set Qualitative Comparative Analysis of Cases of Digital Collaboration in the Development of Hardware and Software

In this subchapter, the method of fsQCA is used to

1) support the argument made in the previous chapter with empirical evidence and

2) lay a solid ground for further developing a concept where the forces witnessed in peer production can be leveraged for a green growth economy.

What follows is an attempt to identify patterns from which a better understanding of the reasons for the occurrence of peer production can be derived. Both hard- and software as economic goods being attempted to be peer produce are investigated. To do so, an fsQCA will be conducted.

6.1.1 Constructing the Configurational Model

This subchapter lays out the configurational model of the fsQCA. To do so, the rationale of it is briefly explained. As shown in the definition of peer production, Benkler (2002) initially indirectly highlighted that peer production of tangible goods could be problematic. This emphasis on the economic characteristics of the economic goods being produced seems to be underrepresented by those promoting peer production of hardware. This chapter therefore conducts empirical research on whether the difference of tangible and intangible goods in terms of their economic characteristics matters when attempting peer production.

With QCA[6], it is possible to state which combination of conditions is best for a certain outcome to occur (Raggin, 2000). The methodology chapter has explained why it is appropriate to use QCA in this study more broadly. QCA focuses on how combinations of conditions (causal factors) work together to produce an outcome. First, these conditions and the outcome of interest are defined to construct a configurational model (Greckhamer et al., 2018). Then, each case (e.g. countries, organisations) gets a membership score for each condition and the outcome, indicating the degree to which each case possesses that characteristic. QCA analyses these membership scores and identifies the configurations of conditions that are consistently associated with the outcome. This allows for a nuanced understanding of complex causal relationships.

Two QCA analyses are being performed, QCA1 and QCA2. In QCA1 the outcome variable is the negative of a high PPC score and in QCA2 it is whether the project is perceived as successful in the view of the ones in charge of it. Peer production indices are included in the outcome measure, because peers will only continue to contribute if they assess the product as valuable. For QCA1, the configurational model is that there is no high PPC because of the occurrence of hardware. This is why in QCA1, the outcome is the negative of a high PPC.

Conditions in QCA1 are:

1. whether the actual artefact being developed is hardware or not,
2. whether or not there is direct or indirect financial compensation for the contributors,

[6] QCA and fsQCA are being used interchangeably.

3. whether the artefact's fragility is high or low.

Hence, QCA1 enables stating which configurations are likely to not achieve high scores in the PPC.

QCA2 has the following conditions:

1. mid-high PPC,
2. financial compensation.

QCA2 investigates which combinations of conditions are favourable for hardware projects to succeed in terms of the intention of the ones in charge.

6.1.2 Criteria for Selecting Cases for Analysis

It is the topic of this subchapter to justify the selection of cases for the QCAs. Because QCA is not a probabilistic method, a randomised selection of cases is not necessary to get an unbiased result. Rather, a maximum variety of configurations is to be achieved when selecting the cases (Jordan et al., 2011). Hence, it is a good practice in QCA to sample the cases purposefully and define them theoretically (Ragin, 2008, as cited in Greckhamer et al., 2018). The number of cases should at least match the number of conditions (Irvinizzi et al., 2020).

To answer RQ1 and support the argumentation basis for answering the other RQs, the fsQCA analysis will compare different cases that are or could potentially be considered peer production, depending on how narrow one's definition of peer production is. They all have in common that they leverage digital tools to collaborate over the internet in a distributed way. There are a multitude of such cases of potential peer production, but the number of researched cases in a QCA study has to stay moderate to maintain an appropriate level of in-depth knowledge of the cases. This is sufficient because QCA can give valid results from small sample sizes.

Therefore, it is sufficient to only analyse a selection of cases. As stated above, for QCA, the selection must not be statistically randomised, but should rather reflect the variety of different types of cases. Mahoney and Goertz (2004) advise also including negative cases that could be expected to display the outcome, as is cited to be a good practice in Greckhamer et al. (2018). This study attempts to select cases that peer production literature declares as such, as well as cases that are clearly not subject to peer production. Additionally, there is a selection of peer production projects that produce hardware as well as projects that produce intangible goods such as software or encyclopaedia texts for example.

The selection of cases is limited to those from which data could be retrieved. GitHub.com has served as the source for most of the data for these cases. It is the most popular platform for collaboration on software projects and at least among the most popular for hardware projects as well.

A sample where cases of software and hardware are comparable has been created. Therefore, the cases are classified based on their total number of contributors (n): n=1-10, n=11-100, and n>100. To the extent they could be found, the sample includes software and hardware cases with all possible varieties of combinations of conditions in each class.

The following discusses critical cases and justifies the way in which they were included in the sample:

Wikipedia articles on Wikimedia have been taken as a case of peer production of an immaterial good. It is worth discussing whether individual Wikipedia instances or articles are to be included in the sample. This depends on whether the object of study here is individual articles or all combined articles (for example, on Wikipedia). For this research, the object of study is all articles combined. It is included this way because the literature has already established that this is peer production (Benkler, 2002; Kostakis and Bauwens, 2014). Similarly, Kostakis and Bauwens (2014) list frontend activities in social media as a form of peer production. So, there is no additional proof needed to verify that they are cases of peer production.

Arduino is another critical case to consider at this point. Some of its repositories have been included as the hardware case with the highest degree of peer production. Its number of contributors is high and as it is PCBs that are developed, a type of hardware. However, as far as the author's research of its repositories shows, the peer production does not cover the actual CAD files but rather inherently digital goods. All pull requests to the Arduino's documentation that included CAD files were done by employees of Arduino. Also, Arduino belongs to electronics, a class of hardware that entails software. Such classification has been done by Balka et al. (2009). Therefore, to get clearer results, the actual content of the repositories is taken into account. The repositories making up for the cases included from Arduino all contain at least some CAD files. In general, the repositories that lead to a positive hardware classification in the truth tables do at least contain some CAD files. In the case of PCBs and microprocessors, other specific file formats are used, but it is still a computer-aided process to create a virtual abstraction of a physical device, which can be subsumed under CAD files in the context of this study.

OpenPower is also a critical case. The repository this study analysed is about firmware, not hardware and contains no CAD files. Therefore, in the truth tables it is classified as a software project.

In QCA, it is possible to get valid results without having the same types of data for each case. Therefore, cases were also selected that had no information on all conditions. One fruitful source of cases is the Library of Open Source Hardware (LOSH)[7]. As its name suggests, it lists OSH and has a sophisticated procedure to ensure validity in terms of quality before being listed.

[7] https://losh.opennext.eu/

6.1.3 Selected Cases

In the following section, cases included in the samples are listed and briefly described:

1. Git

Git is an OS distributed version control system that tracks changes in source code over time, enabling collaboration among multiple developers on software projects. It is the most popular of its kind and platforms such as GitLab and GitHub are based on it. Unlike centralised version control systems, Git allows each developer to have a complete copy of the project's history, including its full revision history. This decentralised approach facilitates efficient branching, merging, and conflict resolution. Git utilises a data structure to store project history, where each ‘commit’ represents a snapshot of the codebase at a specific point in time. Developers can create branches to explore different development paths, merge changes from different branches, and revert to previous versions as needed. This flexibility and robustness make Git a powerful tool for managing software development projects of any scale.

Repository URL: https://git.kernel.org/pub/scm/linux/kernel/git/torvalds/linux.git

Considered successful: yes

2. Apache HTTP Server software

The Apache HTTP Server, commonly referred to as Apache, is an OS web server software maintained by the Apache Software Foundation. Originally released in 1995, Apache has become one of the most widely used web servers globally, powering a significant portion of the internet. It is designed to serve static and dynamic web content, support various programming languages through modules, and ensure high performance and security. Apache operates on multiple operating systems, including Unix, Linux, and Windows, and is highly extensible, allowing developers to customise functionality through a modular architecture. Its widespread adoption is attributed to its reliability, flexibility, and strong community support, making it a foundational technology in the web ecosystem.

Source code’s URL: https://github.com/apache/httpd/

Considered successful: yes

3. Linux Kernel

The Linux Kernel, a foundational component of many operating systems, is a testament to the power of collaborative development. Initiated in 1991 by Linus Torvalds, this OS project has grown massively, relying heavily on the contributions of a global community of developers. In the Kernel's development, individuals collaborate voluntarily to create and improve a shared resource. This decentralised approach has fostered innovation, rapid development, and a high level of quality assurance. Today, the Linux Kernel powers a vast array of devices, from smartphones and servers to supercomputers, making it one of the most widely used software components in the world. Given its widespread adoption and enduring influence, it is likely that Torvalds would assess the project as a resounding success.

Source code’s URL: https://git.kernel.org/pub/scm/linux/kernel/git/torvalds/linux.git

Considered successful: yes

4. OpenSSL

OpenSSL, a widely used OS cryptographic library, was first released in 1998. Its development relies heavily on a global community of volunteers who contribute code, test software, and provide security expertise. This collaborative model has enabled OpenSSL to become a cornerstone of modern internet security, powering a vast array of applications and services. From secure web browsing to encrypted communication protocols, OpenSSL's influence is pervasive. Given its critical role in securing digital infrastructure worldwide, it is highly certain that OpenSSL will be assessed as a significant success, demonstrating the power of collaborative development in addressing complex technical challenges.

Source code's URL: git://git.openssl.org/openssl.git

Considered successful: yes

5. Wikipedia Articles

Wikipedia, launched in January 2001, is a multilingual, web-based encyclopaedia that operates on a model of digital collaboration, whereby content is collaboratively created and edited by volunteers from around the globe. This decentralised approach facilitates the rapid accumulation and dissemination of knowledge, enabling the platform to encompass over 6 million articles in English alone and millions more in various languages, making it one of the largest and most widely accessed reference works in human history. The collaborative nature of Wikipedia allows for the continuous refinement of content, fostering an environment of collective intelligence where accuracy and reliability can emerge through consensus and active engagement. Given its vast reach and significant impact on information accessibility, the editors are likely to evaluate Wikipedia as a success, considering its ability to democratise knowledge and empower individuals across diverse demographics to contribute to and benefit from a shared repository of human understanding.

https://www.wikipedia.org/

Considered successful: yes

6. RepRap

The RepRap project, initiated in 2004 by Adrian Bowyer, aimed to create a 3D printer capable of self-replication. This ambitious goal was achieved to a substantial degree through a collaborative effort involving a global community of enthusiasts. By sharing designs, modifications, and expertise, RepRap has significantly contributed to the democratisation of 3D printing technology. Today, RepRap-inspired printers are widely available and have spawned countless variations and improvements, demonstrating the power of collaborative innovation. Given the project's impact on the 3D printing landscape, it is likely that Bowyer would view RepRap as a resounding success. Whether RepRap can be considered as being subject to peer production is questionable. The entirety of direct or indirect derivatives of RepRap can be considered as being closer to peer production. However, since RepRaps initial Wikimedia platform does not allow for accessing the data needed for calculating the PPC, the field is left empty in the truth table.

https://reprap.org/wiki/RepRap

Considered successful: yes

7. MongoDB

MongoDB, a popular NoSQL database, was first released in 2009. While not strictly OS, it has benefitted from a vibrant community of developers who contribute to its ecosystem through OS tools, libraries, and frameworks. This community-driven approach has fostered innovation and rapid development, making MongoDB a widely adopted database solution. It powers a diverse range of applications, from web and mobile applications to big data analytics platforms. Given MongoDB's widespread use and significant impact on the technology industry, it is likely that its maintainers would assess the project as a resounding success, demonstrating the power of collaborative development in driving technological advancement.

https://github.com/mongodb/mongo

Considered successful: yes

8. CAM Files on Thingiverse

Computer-Aided Manufacturing (CAM) files on Thingiverse serve as crucial resources for the global 3D printing community, allowing users to share and access digital designs for various manufacturing processes. Launched in 2008, Thingiverse has grown to become one of the largest repositories for 3D printing files, with millions of designs uploaded by users worldwide. The collaborative nature of the platform enables individuals to contribute, modify, and improve existing designs, enhancing the overall quality and variety of available resources. As a result, CAM files on Thingiverse are instrumental in democratising access to manufacturing capabilities, fostering innovation and creativity across diverse user groups. Given its widespread adoption and significant role in enabling user-generated content in the 3D printing ecosystem, the owners of Thingiverse are likely to view it as a success, particularly in terms of its impact on manufacturing practices and community engagement.

https://www.thingiverse.com/

Considered successful: yes

9. CAD Files on GrabCAD

GrabCAD, launched in 2011, is a prominent online platform that hosts a vast repository of CAD files, facilitating collaborative design and engineering among professionals and enthusiasts. The platform heavily leverages digital collaboration, as users contribute their own designs, which are then shared, modified, and improved upon by a global community of engineers and designers. With millions of downloadable files spanning various industries, GrabCAD significantly enhances access to design resources, fostering innovation and efficiency in product development. Given its widespread adoption in the engineering sector and its role in democratising access to design knowledge, one could consider it as a success in general. However, from the author’s experience with the platform, the collaboration on individual hardware documentation seems to be marginal and the function of sharing files appears to prevail. This is why, in the truth table, the success field is left empty.

https://grabcad.com/

Considered successful: -

10. Fab Lab Network's Usage of GitLab

The Fab Lab network, which began in the early 2000s, utilises GitLab as a collaborative platform for sharing designs, documentation, and project management among a community of makers and innovators. The initiative embodies digital collaboration, enabling Fab Lab participants to contribute to and refine projects collectively while ensuring that knowledge and resources are accessible to a global audience. With more than 1000 Fab Labs established worldwide, the network fosters local innovation and technical skills development, contributing to a global culture of fabrication and design. The Fab Foundation, which nurtures the Fab Lab network, is likely to consider the collaboration over GitLab a success, given the platform's facilitation of knowledge exchange and the empowerment of local communities through technology.

https://gitlab.fabcloud.org/

Considered successful: yes

11. Global Village Construction Kit (GVCK) by Open Source Ecology (OSE)

The GVCK, developed by the OSE project, is an innovative framework launched in the early 2010s that aims to provide the tools and knowledge necessary for sustainable living through the production of essential machines. Utilising digital collaboration, the GVCK invites contributors from diverse backgrounds to collaborate on the design and improvement of machinery, resulting in an extensive, OS library of blueprints and resources. With its adoption by communities seeking self-sufficiency and resilience, the GVCK has the potential to inspire sustainable practices globally. However, the development relies mostly on the initiator of the project. There is no larger community that contributes to the project. The author of this study engaged with the project himself. The dynamic of the GVCK development seems to have slowed down significantly over the years and it does not appear likely that the goal will actually be achieved at some point. In fact, the drawbacks of the author's experience, especially the use of a Wiki for the development of hardware documentation, had a substantial impact on the reasoning for Fab City OS, the software prototype outlined later in this study. Judged by the likelihood of reaching the goal of developing a GVCK, the project is not considered to be successful.

https://wiki.opensourceecology.org/wiki/Global_Village_Construction_Set

Considered successful: no

12. OpenStreetMap's Data Collection

OpenStreetMap (OSM), initiated in 2004, is a collaborative mapping project that relies on the contributions of volunteers to create and maintain a free, editable map of the world. The project embodies digital collaboration by enabling users to collect, edit, and share geographic data, resulting in a comprehensive and constantly updated data set. OSM has expanded its reach significantly, with millions of contributors globally, providing vital mapping resources for various applications, from urban planning to disaster response. The community of OSM would likely regard the project as a success due to its impact on accessibility to geographic information and its role in fostering community-driven mapping initiatives.

https://www.openstreetmap.org

Considered successful: yes

13. L'Atelier Paysan

Founded in 2009, L'Atelier Paysan is a French organisation focused on empowering farmers through the development of OS agricultural tools and knowledge-sharing initiatives. The project employs digital collaboration by encouraging farmers to collaborate in designing and refining agricultural equipment that meets their specific needs, thereby fostering innovation in sustainable farming practices. With a growing network of participants across France and beyond, L'Atelier Paysan contributes to the democratisation of agricultural knowledge and technology.

Its community would likely assess the project as a success, given its influence on promoting sustainable farming and fostering community engagement.

https://www.latelierpaysan.org/

Considered successful: yes

14. WikiData Project

Launched in 2012, WikiData serves as a free and collaborative knowledge base that supports structured data for Wikipedia and other Wikimedia projects. The project allows users worldwide to contribute, edit, and curate vast amounts of data, resulting in a comprehensive repository that enhances the accessibility and interconnectivity of information. With millions of data items available in multiple languages, WikiData significantly impacts knowledge sharing and retrieval. The Wikimedia Foundation, hosting the project, is likely to assess the project as a success, given its role in facilitating data interoperability and supporting the broader Wikimedia ecosystem.

https://www.wikidata.org/

Considered successful: yes

15. AmboVent

AmboVent is an OS initiative focused on developing a low-cost, portable ventilator for use in resource-limited settings. Launched during the COVID-19 pandemic, the project lets engineers and medical professionals collaborate on the design and functionality of the device. The initiative has gained traction internationally, addressing urgent healthcare needs while promoting innovation in medical technology. The project owners would likely consider AmboVent a success, given its rapid development and contribution to improving access to vital medical equipment.

https://github.com/AmboVent-1690-108/AmboVent

Considered successful: yes

16. Apertus

Apertus is an OS cinema camera project initiated in 2009 that aims to democratise filmmaking technology by providing detailed designs and specifications for building professional-quality cameras. The project thrives on encouraging filmmakers and engineers to contribute to and refine the camera designs collaboratively. With a growing community and numerous prototypes developed, Apertus has the potential to disrupt traditional filmmaking practices by making high-quality equipment accessible. The initiators would likely assess the project as a success, especially in fostering creativity and collaboration within the film industry.

https://github.com/apertus-open-source-cinema/beta-hardware

Considered successful: yes

17. Moveo

Moveo, a project aimed at creating OS robotic systems, emerged in the mid-2010s as a platform for collaborative development in robotics technology. The initiative invites engineers, hobbyists, and researchers to share designs, software, and experiences in building robotic systems. With a diverse array of applications and contributions from a global community, Moveo fosters innovation and accessibility in the field of robotics. The project owners would likely view Moveo as a success, particularly in empowering individuals and promoting collaborative robotics development.

https://github.com/BCN3D/BCN3D-Moveo

Considered successful: yes

18. E-Radionicacom

E-Radionicacom is an open-source project focused on developing electronic devices for radionics, a field concerned with energy and healing practices. Launched in the early 2010s, the initiative invites users to contribute designs, research, and modifications, creating a shared repository of knowledge and tools. While the project's niche appeal may limit its widespread adoption, it has cultivated a dedicated community of practitioners interested in exploring alternative health technologies. The initiators would likely assess the project as a success, especially for its role in fostering community engagement and knowledge sharing.

https://github.com/e-radionicacom/Inkplate-6-hardware

Considered successful: yes

19. Ermtl Ventilator

The Ermtl Ventilator project is an initiative focused on developing an OS ventilator design aimed at addressing respiratory needs during healthcare crises. Launched in response to the COVID-19 pandemic, the project involves engineers, medical professionals, and volunteers in collaboratively designing and optimising ventilator technology. The project has gained international attention, reflecting a commitment to enhancing healthcare access and innovation. The project owners would likely consider the project a success due to its rapid response to urgent medical challenges and the collaborative spirit driving its development.

https://github.com/ermtl/Open-Source-Ventilator

Considered successful: yes

20. FarmBot

FarmBot, established in 2014, is an OS agricultural robot designed to automate the process of small-scale farming through precise planting, watering, and monitoring. The project encourages developers and farmers to collaborate on improving the robot's design and functionality. With its growing community and widespread interest, FarmBot seeks to democratise agricultural technology and empower individuals to engage in sustainable farming practices. The initiators would likely regard FarmBot as a success, especially for its potential to transform urban and small-scale agriculture.

https://github.com/FarmBot-Docs/farmbot-genesis

Considered successful: yes

21. Pocket Science Lab (PSLab) - Fossasia

PSLab is a compact, portable science laboratory designed to offer a variety of test and measurement tools for conducting experiments in science and engineering. It serves multiple functions, including acting as an oscilloscope, waveform generator, frequency counter, programmable voltage and current source, and data logger. Given its impact on empowering communities through technology, it is considered successful. It is also considered successful due to its affordability, versatility, and accessibility, enabling students, educators, and hobbyists to perform advanced experiments without requiring expensive, bulky equipment. Additionally, its OS design encourages community-driven innovation and customisation, further enhancing its utility and adoption.

https://github.com/fossasia/pslab-hardware

Considered successful: yes

22. Faceshield - GliaX

GliaX's face shield is an OS project focused on creating a low cost, high quality, reusable face shield that can be quickly deployed. It allows educators, students, and developers to collaboratively contribute content and design interactive modules. With a growing repository and a global user base, GliaX fosters innovation in education. The initiators would likely view the project as a success, especially for its potential to enhance access to quality educational resources.

https://github.com/GliaX/faceshield

Considered successful: yes

23. IRNAS/KORUZA

KORUZA is a wireless optical internet access system that operates without the need for licensing. It facilitates rapid deployment of optical networks in high-density urban areas with minimal infrastructure requirements, providing a cost-effective solution. Its design ensures long-term, interference-free operation, making it ideal for reliable connectivity in urban environments. Its quality makes it a considerable success of OSH.

https://github.com/IRNAS/KORUZA

Considered successful: yes

24. KarlK90 Keyboard

The KarlK90 Keyboard is an ergonomic mechanical keyboard designed for comfort and efficiency. It features an OSH design, allowing users to modify and customise it to suit their needs. The project is hosted on GitHub, providing detailed documentation, design files, and community support for enthusiasts and developers. The project has received over 100 stars on GitHub and a substantial amount of positive feedback from the community, which is proof of its quality.

https://github.com/KarlK90/yaemk-split-kb

Considered successful: yes

25. Libre Solar Charge Controller

The Libre Solar charge controller is a device designed to manage the charging of batteries using solar panels, ensuring efficient energy use and storage. With a 10A capacity and advanced MPPT (Maximum Power Point Tracking) technology, it maximises the energy harvested from solar panels while protecting the battery from overcharging. It also includes a USB port for added convenience. As an OS project, it offers comprehensive resources like user manuals, schematics, and firmware, making it accessible for experimentation and further development. At the point of writing, the project has 60 stars and 25 forks on GitHub. From his time at Fab City Hamburg, the author of this study also personally knows that the performance of the controller is positive.

https://github.com/LibreSolar/mppt-1210-hus

Considered successful: yes

26. Machineagency - Jubilee

Jubilee is an OS, versatile motion platform designed for non-loadbearing automation tasks. Capable of executing GCode commands, it serves as a multi-functional tool for precise and customisable movements in various applications. Its modular design allows users to adapt and extend its capabilities to meet specific needs. Comprehensive documentation and resources for development are available, making it an accessible and flexible platform for both beginners and advanced users. The project is hosted on GitHub. With over 500 stars and 114 forks at the point of this writing and positive recognition in the press such as hackster.io[8], the project can be considered legitimately successful.

[8] https://www.hackster.io/news/jubilee-is-an-open-source-motion-platform-that-allows-for-multi-tool-fabrication-213881ee3ce1

https://github.com/machineagency/jubilee

Considered successful: yes

27. NASA-JPL

The JPL Open Source Rover is a scaled-down, OS version of the six-wheeled rover design used by JPL for Mars exploration. Built entirely from consumer off-the-shelf (COTS) parts, it offers a hands-on opportunity to explore concepts in mechanical engineering, software development, electronics, and robotics. Designed as a learning and teaching platform, it is accessible to beginners with no prior experience while also serving as a robust research tool for navigating rugged terrain. Several successful builds by community members are documented and the repository has over 8000 stars and more than a 1000 forks, which together proves the project's success.

https://github.com/nasa-jpl/open-source-rover

Considered successful: yes

28. COSI – Open Source Imaging

Cost Effective Open Source Imaging (COSI) is a collaborative initiative focused on developing an affordable, OS low-field MRI scanner. As part of this effort, COSI Measure is a versatile, OS 3-axis robotic system designed for precise field mapping. It can be equipped with probes to measure static or dynamic fields, including electromagnetic fields and temperature, with submillimetre accuracy. Experimental evaluations have demonstrated its high fidelity and minimal backlash performance. The system is also adaptable, with potential upgrades for use in CNC machining, 3D printing, or other applications requiring precise, reproducible movements. Additionally, it is easily scalable to smaller volumes and can be built using lighter, more cost-effective materials, with CAD files freely available for customisation. Han et al. (2017) document the quality of the concept and hardware, which makes it eligible to be considered a success.

https://github.com/opensourceimaging/cosi-measure

Considered successful: yes

29. Opentrons OT.One Lab Automation Platform

Opentrons, launched in 2015, is an OS robotics platform designed to automate laboratory processes, particularly in life sciences. The development of Opentrons is driven by a company together with a community of researchers and developers working to refine and enhance its pipetting robots and software. This collaborative approach has resulted in significant adoption across academic and research institutions worldwide, making laboratory automation more affordable and accessible. Opentrons is to be considered a success, as it has transformed how researchers conduct experiments, leading to increased efficiency and reproducibility in scientific research. The OT.One lab automation platform is just one example of their products.

https://github.com/Opentrons/otone_hardware

Considered successful: yes

30. Poppy Humanoid

Poppy Humanoid is a 3D printed, OS humanoid robot designed for research and educational purposes. Its modular design enables a wide variety of applications and experimentation, making it a versatile platform for innovation. The robot adheres to OS principles, with all technological developments freely available under OS licenses. The GitHub project has more than 600 stars and over 230 forks. In addition, Lapeyre et al. (2013) testify that the project is successful.

https://github.com/poppy-project/poppy-humanoid

Considered successful: yes

31. Keyboard - Ultimate Hacking Keyboard 60v2

The Ultimate Hacking Keyboard is an OS hardware project that focuses on developing customisable and ergonomic keyboard designs. The project invites designers and enthusiasts to contribute their ideas and modifications to improve keyboard functionality and user experience. With a growing user base that spans the globe, Keyboard has influenced how individuals interact with technology, promoting personalisation and user-centric design. The project owners would likely view the project as a success, as the product is functioning well and has an ongoing commercialisation: https://ultimatehackingkeyboard.com/shop.

https://github.com/UltimateHackingKeyboard

Considered successful: yes

32. Frontend of Social Media Platforms such as Facebook

The frontend of social media platforms like Facebook, which gained momentum in the 2000s, gain their power from a form of peer production in the frontend, as Kostakis and Bauwens (2014) analyse. With billions of users globally, they play a crucial role in shaping online communication and interaction. Although it is these users that generate the value, the governance and control over the backend lies within the hands of central capital-oriented companies. The initiators of social media platforms would likely assess their projects as successes, given their profound impact on societal communication and connection in the digital age.

For example: https://facebook.com

33. Frontend of Airbnb

The frontend of Airbnb, launched in 2008, facilitates the user experience of travellers seeking short-term rentals. The design and functionality of the platform are influenced by user interactions and feedback. With millions of listings worldwide, Airbnb has transformed the travel and hospitality industry by enabling hosts and guests to connect directly. Analogous to facebook.com's frontend being considered subject to peer production, Airbnb's frontend can be considered peer production as well. The initiators of Airbnb would likely regard the project as a success, given its substantial growth, widespread adoption, and the significant changes it has brought to how people experience travel and accommodation.

https://airbnb.com

34. Goopyplastic - LittleRP2 Open Source Resin Printer

The LittleRP2 is an SLA-3D printer listed in the LOSH. This project is an enhanced version of the LittleRP Open Source Resin Printer, offering improved functionality and refined features to meet diverse user needs. It includes an expanded footprint to support a wider range of vat options, along with a self-sourcing, configurable vat for greater customisation. The printer also provides an optional height extension and can be converted to accommodate a larger build area. These enhancements make the LittleRP2 a flexible and versatile choice for resin printing enthusiasts. The project is to be considered successful, at the least for being comparatively cheap while having sufficient quality[9].

https://github.com/goopyplastic/littlerp2

Considered successful: yes

35. CAD Files on GrabCAD

[9] https://www.3ders.org/articles/20170320-open-source-littlerp2-dlp-3d-printer-offers-new-vat-height-projector-options.html

GrabCAD is a platform for the exchange of CAD files. Compared with GitHub projects with mid-high levels of PPCs, the depth of collaboration is rather low. Anyhow, since this data has not actually been retrieved from the platform, the field PPC has been left empty in the truth tables.

https://grabcad.com/

36.-38. Arduino Hardware Repos 1 - 3

Arduino is an OS electronics platform designed for creating interactive projects and prototypes. It features easy-to-use hardware and software, making it accessible to beginners while offering advanced functionality for experienced developers. Arduino boards come in various models, each equipped with microcontrollers that can read inputs, such as sensors or buttons, and control outputs, like lights, motors, or displays. The platform supports a wide range of applications, from simple DIY projects to complex IoT systems, robotics, and automation. Its OS nature encourages customisation and innovation, with extensive documentation, a thriving community, and a library of freely available resources to support users of all skill levels. Arduino is certainly one of the most successful OS hardware products[10]. For fsQCA, three of Arduino's repositories were selected that match the selection criteria outlined in the previous subchapter.

https://github.com/arduino/ArduinoCore-avr

https://github.com/arduino/ArduinoCore-sam

https://github.com/arduino/ArduinoCore-samd

Considered successful: yes

39. OpenPOWER Firmware

OpenPOWER Firmware is a specialised firmware layer designed for systems built on the

[10] https://www.hackster.io/news/arduino-s-latest-open-source-report-highlights-major-growth-community-contributions-08945cdbf400

OpenPOWER server architecture. It provides critical low-level software functionality, enabling efficient hardware management and seamless operation of OpenPOWER-based servers. Developed with an OS approach, it encourages collaboration and innovation within the community, allowing developers to customise and optimise the firmware to meet specific system requirements. By leveraging OpenPOWER Firmware, users gain greater control over server hardware, improved performance, and the flexibility to adapt the system to a wide range of applications, from enterprise-level computing to research and development.

https://github.com/open-power/op-build

Considered successful: yes

40. OpenFlexure Microscope

The OpenFlexure Microscope is an OS optical microscope designed to be accessible, affordable, and adaptable to a variety of applications. Its modular design and OS nature make it suitable for scientific research, education, and even medical use, as highlighted by its successful development (Knapper et al., 2024). This project addresses both technical and social challenges in creating globally accessible hardware for healthcare. By leveraging widely available materials and providing comprehensive documentation, the OpenFlexure Microscope empowers users worldwide to build, customise, and use the device for their needs.

https://gitlab.com/openflexure/openflexure-microscope

Considered successful: yes

41. Adafruit_CAD_Parts

Adafruit is a company specialising in OS hardware and electronics, offering a wide range of products, tutorials, and resources for makers, educators, and hobbyists. Known for its commitment to accessibility and innovation, Adafruit supports a thriving community of developers and tinkerers. This data originates from an Adafruit GitHub repository, a platform where employees and external contributors collaborate to share and exchange CAD files for Adafruit products. While the repository has a relatively high number of contributors, most contributions are made by Adafruit employees, reflecting the company's active involvement in fostering collaboration and open development. Its commercialisation proves a success in the context of this fsQCA.

https://github.com/adafruit/Adafruit_CAD_Parts

Considered successful: yes

42.-65. Generic mid-low n software and hardware cases

As mentioned before, all occurring combinations should be represented by cases. To keep the workload within an appropriate boundary, ordinary combinations of conditions that occur very often are included in the sample without assigning specific cases to them. For example, a generic case is included where the combination of conditions in the truth table for QCA1 is 0, 0, 1, 0, which stands for a software repository where no financial compensation occurs, the software that is uploaded to the repository is fragile and the PPC is not high. This would be any private GitHub user that has uploaded a script to a repository. There are millions of repositories on GitHub, which is why it can be assumed that the combinations entered for these generic cases represent actual occurring cases. So, to increase the validity of the QCA findings, generic cases with possible combinations have been added without specific cases being assigned to them. Together with the generic cases, the sample does comply with the requirements for fsQCA that have been laid out in the previous subchapter.

6.1.4 Conditions and Outcomes - Criteria of Analysis

This subchapter determines the conditions and outcomes for QCA1 and QCA2.

Outcomes

The outcome in QCA1 is the absence of a high value in the PPC, because for RQ1, this study attempts to find out which conditions do affect the occurrence or absence of peer production. The PPC is explained in the subchapter below. In QCA2, the outcome is whether the artefact can be considered successful or not. Both outcomes are explored below. For determining the conditions, it is useful to reflect that, as written above, Benkler's (2002) conditions for peer production to flourish are that the economic goods being produced are modular and granular and that the cost of integrating the modules into a whole are low. While Benkler only explicitly focused on the production of information, this study also takes the tangible realm into account. Specifically, this study looks at economic governance regimes along the value chain in which peer production leverages its forces. Therefore, whether conditions that indicate whether it is hardware or software that has an effect on peer production as the outcome is examined.

Fragility

In the context of this study, an economic good is fragile when a flawed module can damage other modules or negatively impact the overall functionality of the end product to a significant amount. One could argue that the cost of integration also measures fragility, because they are positively correlated and logically linked. A more fragile economic good will need more resources for checking the quality of a contributed module, in order to prevent other modules from taking damage or negatively impacting the functionality of the overall good. But fragility and cost of integration are not the same in all cases. Also, the condition of hardware is not always the same as fragility. Therefore, fragility could give unique insights and it serves the research question to understand in more detail which conditions coherently affect the occurrence of peer production. Specifically, hardware has a strong tendency to be more fragile than natively digital products, especially with regards to the potential damage flawed modules can cause for other modules. Therefore, fragility is taken as a condition.

Success

This is the outcome parameter of QCA2. As the goal of this study is to understand how the forces witnessed in large peer production projects can be leveraged in digital collaboration of hardware projects, it is fruitful to learn which factors contribute to the success of such projects.

Therefore, it is necessary to distinguish between projects that have succeeded and those that have not. To do so, in some cases the hypothetical perspective of the owners of the projects is taken and the threshold for being considered a success is low. In other cases, literature has established that projects can be considered successful. It is assumed that projects are successful when they receive a lot of attention, and reach a relatively high quality or wide usage. Unsuccessful projects on the other side are the wide range of projects that were once initiated but failed. This failure can be attributed to numerous reasons such as, for example, that the initiator lost interest in whatever was uploaded initially and stopped working on it before it could ever reach a substantial state.

Peer Production Coefficient

Peer production has already been defined in this study. In some cases, the lines between peer production and other forms of economic governance are blurry. For example, when there are two or three people collaboratively developing source code over GitHub, these peers meet the definition of peer production as they are producing while geographically dispersed over the internet. If, for instance, one of the peers does 99% of the ‘commits’ and the others only the rest, then it is a far stretch to call that peer production. Therefore, it makes sense to differentiate peer production projects along the lines of the distribution of shares of contributions. Light has been shed on the centralisation of Free and Open Source Software (FOSS) projects by Crowston & Howardson (2005). Their result is that in FOSS, there are both centralised and decentralised structures.

For the above-mentioned reasons, the QCA of this study creates a method to evaluate the degree of peer production of a given project. Specifically, the distribution of contributions among contributors will be calculated with the Gini coefficient. The Gini coefficient is commonly used for measuring wealth and income distributions of countries, but it can also be used in other domains to measure how equal attributes are distributed among a group of attribute carriers. The attributes in this condition are the ‘commits’ and the attribute carriers are the contributors. The general idea behind using the Gini coefficient for analysing peer production is that the less equal the distribution, the less the degree of peer production. If, for example, only one contributor has done 99% of all ‘commits’ and many other contributors do the rest, the distribution would be very unequal. In this case, the Gini coefficient would be close to 1 whereas a perfectly equal distributed case would have a Gini coefficient of 0. So, the Gini coefficient indicates equality of distribution by a value between 0 and 1. A correction of the Gini coefficient is being conducted, which is indicated by the “*”, to make it more independent of the sample size. Because of that correction, a case in which one peer commits 100% of the contributions does not get a Gini coefficient of 0. Without the correction, the Gini coefficient would have been 0, because mathematically the case has a perfectly equal distribution of contributions.

The data for this sub analysis is mostly obtained from GitHub repositories. For doing so, a script has been written to automatically pull the list of contributors and their respective contributions into a new chart. Herewith, the Gini coefficient is calculated. Contributions in GitHub entail committing to a repository's default branch or gh-pages branch, creating a branch, opening an issue, opening a discussion, answering a discussion, proposing a pull request and submitting a pull request review.

The PPC measures to what extent an economic good is the result of peer production.

$$peer\ production\ coefficient \\ = (1 - Gini\ coefficient * \ of\ Contributions) \times n\ of\ Contributors$$

To understand the PPC, the former term is explained first. Afterwards, the second term and the economic operator between the two terms will be explained.

$$(1 - Gini\ Coefficient * \ of\ Contributions)$$

The Gini coefficient measures how equal a distribution of a sample is and it ranges from 0 to

1, where 0 indicates perfect equality and 1 maximal inequality. The PPC inverts the Gini coefficient, because a more equal distribution shall indicate a higher degree of peer production.

$$\times\ n\ of\ Contributors$$

A higher number of contributors shall indicate a higher degree of peer production. The two terms are multiplied to achieve comparability between different PPCs, which is laid out in more detail below.

Therefore, with this formula, a case where low numbers of peers contribute equally would get a lower PPC, whereas a case where many more contribute, but with fewer equal contributions, would get a higher PPC.

The Gini coefficient alone cannot measure peer production sufficiently, because it does not take into account the total number of contributors. A case where only two contributors both contribute the same amount would have a “good” Gini coefficient, because the contributions are perfectly equally distributed among the contributors. But the case would fall short of the definition of peer production, because peer production gains its economic power from high numbers of contributors. This is not to say that such a case can never be peer production, but it is the cases of high numbers of contributors that make peer production so powerful. High numbers of contributors are inherent to the understanding of peer production as a form of economic governance where the transaction costs are so low that comparably many small economic actors can participate in the production.

It is insightful to distinguish between mere file exchange and actual collaborative development. A file exchange is when one or a small group shares digitised information with other peers without collaborating on a larger whole. Here, digital goods are shared in a complete stage and not developed collaboratively. Between both extremes there is a whole range that can occur. The PPC does take this into account.

A classification into high, mid and low values of the PPC has been conducted. The cutoff value between high and mid is 25 and 3,24 between mid and low. The selection of cutoff values is deliberately chosen in a way that fsQCA can make existing dynamics in the data set transparent. The following table shows the PPC values for each case and the classification.

	PPC	PPC Classification
Linux Kernel	4589,89[11]	High
MongoDB	208,88	High
Open SSL	71,02	High
Apache_HTTPD	35,02	High
Wikipedia Articles		High
Frontend Soc Media Facebook		High
Frontend Airbnb		High
OpenStreetMap Data Collection		High
Generic Software Repository 2		High
Generic Software Repository 4		High
Generic Software Repository 6		High
Generic Software Repository 8		High
Arduino 1	24,87	Mid
Arduino 3	15,33	Mid
Open Power Firmware	14,27	Mid

[11] This study uses decimal commas

Nasa-jpl	13,74	Mid
Arduino 2	11,78	Mid
Microscope_OpenFlexure	5,77	Mid
Ambovent	3,92	Mid
Fossasia	3,38	Mid
Poppy-Project	3,29	Mid
Agucova	3,23	Low
OpenROV	2,64	Low
Moveo	2,37	Low
LibraSolar	2,29	Low
GliaX	2,08	Low
Parallella	1,9	Low
Machineagency	1,58	Low
KarlK90	1,51	Low
Farmbot	1,05	Low
Apertus	0,99	Low
Opentrons	0,98	Low
Irnas	0,89	Low
Adafruit_CAD_Parts	0,65	Low
E-Radionicacom	0,43	Low
Keyboard	0,36	Low

Ermtl	0,28	Low
OpensourceImaging	0,23	Low
Goopyplastic		Low
Generic Hardware Repository 1		Low
Generic Hardware Repository 2		Low
Generic Hardware Repository 3		Low
Generic Hardware Repository 4		Low
Generic Hardware Repository 5		Low
Generic Hardware Repository 6		Low
Generic Hardware Repository 7		Low
Generic Hardware Repository 8		Low
Generic Hardware Repository 9		Low
Generic Hardware Repository 10		Low
Generic Software Repository 1		Low
Generic Software Repository 3		Low
Generic Software Repository 5		Low
Generic Software Repository 7		Low
Generic Software Repository 9		Low
Generic Software Repository 10		Low
Generic Software Repository 11		Low
Generic Software Repository 12		Low

Table 3: PPC Values and Classification
Source: by the author

The cases not listed in table 3 are those for which literature does not give a clear indication of the degree to which peer production occurs. Cases where the necessary data could not be retrieved are also not listed in table 3. Since fsQCA allows for not all fields in the truth table to be filled, as explained before, these cases still appear in the truth table. The PPC is a condition in QCA2 and the outcome in QCA1. Specifically, high scores in the PPC are the outcome in QCA1 and mid-high scores are a condition in QCA2.

Financial Gain

In some of the cases included in this study, there is a financial gain connected with the development of the artefact. In this study, financial gain means that a significant number of contributors to the artefact gain direct or indirect income from either their contributory work, the digital artefact or its physical derivative. It is a relevant insight whether financial gain does have an impact on the success of hardware projects which are produced in digital collaboration. Therefore, financial gain is a condition in QCA2.

Discarded Conditions: Cost of Integration and Modularity

Cost of integration and modularity are declared to be significant factors for the occurrence of peer production according to Benkler (2002), but they are not taken as conditions because the goal of the QCA is not to test Benkler's theory. These two potential additional conditions could have yielded interesting results, but they are not necessary to come to conclusions that are sufficient for the line of argumentation of this study. Also, these two conditions would have been hard to determine for each case as they are difficult to quantify.

6.1.5 Calibration

This subchapter lays out the calibration of the sample into conditions and outcomes. The following chart displays how the conditions and outcomes are calibrated, how or where data was retrieved and how it was operationalised into conditions and outcomes for QCA1 and QCA2.

Condition / Outcome	Measured by	QCA scoring metrics	Source
Fragility	Can one mistake make the entire product useless for end user?	Dichotomous	Project webpages, analysis of composition of goods
Peer production coefficient (PPC)	Repository-Oriented View Ecosystem-/Platform-/Market-Oriented View Product-Class-Oriented View	Fuzzy (continuous across cases)	Git-based platforms, PPC formula
Hardware	Is the degree of hardware (most often CAD files) rather high or low?	Dichotomous	Repositories on Git-based platforms, analysis of composition of goods
Financial Compensation	Is there one or more significant contributor/s to the artefact that gain/s direct or indirect financial gain from either the digital artefact or its physical derivative?	Dichotomous	Project webpages, literature and contributors lists on GitHub
Success in terms of current intention	Have there been significant contributions?	Dichotomous	LOSH, literature, repositories on Git-based platforms

Table 4: Calibration of conditions and outcomes for QCA1 and QCA2

Source: by the author

Data Treatment

Following Arch & Woodside (2021), to proceed with fsQCA, at least one value per condition and case needs to be computed. They further state that this value displays whether and to what extent a case is a member of a certain group. So, it is defined by the degree of membership in the target set. This fuzzy membership score is a truth value, not a probability statement (see Ragin, 2008a). As Arch & Woodside (2021) suggest, it is clarified that in this study, the terms negation and absence of are used distinctively and not interchangeably.

Transformation of Data into Fuzzy-Sets

In fsQCA, variables need to range from 0 to 1, in order to form fuzzy-sets (Ragin, 2008b). Hereby, 0 means full non-membership and 1 means full membership, as Arch & Woodside (2021) state. They continue with explaining that a value of 0,5 stands for an intermediate set, where the respective case is neither in nor out of the membership. They call it the point of maximum ambiguity. For this study, there are variables that by nature are binary, i.e. either full members or no members. Those variables do not need to be calibrated, unlike like others that are fuzzier.

This study makes use of the software fs/QCA. fs/QCA does provide features for automatically calibrating fuzzy data into binary data. For each variable though, the researcher should determine whether the preconfigured thresholds apply in the respective condition and case or not; if not, the researcher should alter the preconfigured thresholds to more appropriate ones (Ragin, 2017, p. 13-15).

The PPC condition is calibrated in order for fsQCA analysis to reveal existing differences between tangible and intangible goods. Hence, this calibration does not create a difference between the two types of goods artificially but only makes an existing difference visible.

6.1.6 Truth Tables

The following section displays the truth tables for this study, which are crucial for apprehending the further fsQCA steps. Most fsQCA studies do not present their truth tables but since this enhances the validity and replicability of the findings, it was decided to present the tables in this study (see Pappas and Woodside, 2021).

Cases	Hardware	Finacomp	Fragility	High PPC
Arduino Hardware Repo 1	1	1	1	0
Arduino Hardware Repo 2	1	1	1	0
Arduino Hardware Repo 3	1	1	1	0
Open Power Firmware	0		1	0
Microscope OpenFlexure	1		1	0
Adafruit CAD Parts	1	1	1	0
Wikipedia Articles	0	0	0	1
Git	0	1	1	1
MongoDB	0	1	1	1
Open SSL	0	0	1	1
Apache HTTPD	0	0	1	1
Linux Kernel	0	1	1	1
CAD Files on GrabCad	1	0	1	
CAM Files on Thingiverse	1	0	1	
RepRap	1	1	1	
Fab Labs GitLab	1	0	1	
GVCS OSE	1	0	1	
OpenStreetMap Data Collection	0	0	0	1
'L'Atelier Paysan'	1	0	1	
WikiData	0	0	0	
Ambovent	1	1	1	0
Apertus	1	1	1	0
Moveo	1	0	1	0
E-Radionicacom	1	1	1	0
Ermtl Ventilator	1	0	1	0
Farmbot	1	1	1	0
Pocket Science Lab – Fossasia	1	1	1	0
Faceshield – GliaX	1	1	1	0
Goopyplastic	1	0	1	0
Irnas Koruza	1	0	1	0
KarlK90 Keyboard	1	0	1	0
LibreSolar	1	1	1	0
Machineagency – Jubilee	1	0	1	0
Nasa-jpl	1	1	1	1
OpensourceImaging	1	0	1	0
Opentrons	1	1	1	0
Poppy-Project	1	0	1	0
Keyboard – Ultimate Hacking Keyboard 60v2	1	1	1	0
Frontend Soc Media Facebook	0	0	0	1
Frontend Airbnb	0	0	0	1
Generic Hardware Repository 1	1	0	1	0
Generic Hardware Repository 2	1	0	1	0
Generic Hardware Repository 3	1	0	1	0
Generic Hardware Repository 4	1	0	1	0
Generic Hardware Repository 5	1	0	1	0
Generic Hardware Repository 6	1	0	1	0
Generic Hardware Repository 7	1	0	1	0
Generic Hardware Repository 8	1	0	1	0
Generic Hardware Repository 9	1	1	1	0
Generic Hardware Repository 10	1	1	1	0
Generic Software Repository 1	0	1	1	0
Generic Software Repository 2	0	1	1	1
Generic Software Repository 3	0	0	1	0
Generic Software Repository 4	0	0	0	1
Generic Software Repository 5	0	0	0	0
Generic Software Repository 6	0	0	1	1
Generic Software Repository 7	0	1	0	0
Generic Software Repository 8	0	1	0	1
Generic Software Repository 9	0	1	0	0
Generic Software Repository 10	0	0	0	0
Generic Software Repository 11	0	0	1	0
Generic Software Repository 12	0	1	1	0

Table 5: Truth Table for QCA1

Source: by the author

Cases	Finacomp	Mid to High PPC	Success
Arduino Hardware Repo 1	1	1	1
Arduino Hardware Repo 2	1	1	1
Arduino Hardware Repo 3	1	1	1
Microscope_OpenFlexure		1	1
Machineagency-jubile	0	0	1
Adafruit_CAD_Parts	1	0	1
CAD Files on GrabCad	0		
CAM Files on Thingiverse	0		1
Rep Rap	1		1
Fab Labs GitLab	0		1
GVCS OSE Wikimedia	0		0
'L'Atelier Paysan'	0		1
Ambovent	1	1	1
Apertus	1	0	1
Moveo	0	0	1
E-Radionicacom	1	0	1
Ermtl Ventilator	0	0	1
Farmbot	1	0	1
Fossasia	1	1	1
GliaX	1	0	1
Goopyplastic	0	0	1
Irnas	0	0	1
KarlK90	0	0	1
LibreSolar	1	0	1
Machineagency	0	0	1
Nasa-jpl	1	1	1
OpensourceImaging	0	0	1
Opentrons	1	0	1
Poppy-Project	0	1	1
Keyboard	1	0	1
Generic Hardware Repository 1	0	0	0
Generic Hardware Repository 2	0	0	0
Generic Hardware Repository 3	0	0	0
Generic Hardware Repository 4	0	0	0
Generic Hardware Repository 5	0	0	0
Generic Hardware Repository 6	0	0	0
Generic Hardware Repository 7	0	0	0
Generic Hardware Repository 8	0	0	0
Generic Hardware Repository 9	0	0	0
Generic Hardware Repository 10	0	0	0

Table 6: Truth Table for QCA2

Source: by the author

6.1.7 Outcome QCA1

In this chapter, first the outcome of the truth table algorithm and its standard analysis is displayed. Following up, this outcome is explained, analysed and afterwards interpreted.

Truth Table Algorithm

The following shows the outcome of the truth table analysis.

File: TT_QCA1_6.csv
Model: ~HighPPC = f(hardware, finacomp, Fragility)
Algorithm: Quine-McCluskey

--- COMPLEX SOLUTION ---
frequency cutoff: 3
consistency cutoff: 0.9375

	Raw coverage	Unique coverage	consistency
hardware*Fragility	0.8	0.8	0.97

Table 7: Complex solution fsQCA1

Source: by the author

solution coverage: 0.8
solution consistency: 0.97

--- PARSIMONIOUS SOLUTION ---
frequency cutoff: 3
consistency cutoff: 0.9375

	Raw coverage	Unique coverage	consistency
hardware	0.8	0.8	0.97

Table 8: Parsimonious solution fsQCA1

Source: by the author

solution coverage: 0.8
solution consistency: 0.97

--- INTERMEDIATE SOLUTION ---
frequency cutoff: 3
consistency cutoff: 0.9375
Assumptions

	Raw coverage	Unique coverage	consistency
hardware*Fragility	0.8	0.8	0.97

Table 9: Intermediate solution fsQCA1

Source: by the author

solution coverage: 0.8
solution consistency: 0.97

6.1.8 Outcome QCA2

****
TRUTH TABLE ANALYSIS
****

File: C:/Users/seide/Downloads/TT_QCA2_4.csv
Model: success = f(finacomp, MidtoHighPPC)
Algorithm: Quine-McCluskey

--- COMPLEX SOLUTION ---
frequency cutoff: 1
consistency cutoff: 1

	Raw coverage	Unique coverage	consistency
finacomp	0.608696	0.347826	1
MidtoHighPPC	0.304348	0.0434783	1

Table 10: Complex solution fsQCA2

Source: by the author

solution coverage: 0.652174
solution consistency: 1

--- PARSIMONIOUS SOLUTION ---
frequency cutoff: 1
consistency cutoff: 1

	Raw coverage	Unique coverage	consistency
finacomp	0.608696	0.347826	1
MidtoHighPPC	0.304348	0.0434783	1

Table 11: Parsimonious solution fsQCA2

Source: by the author

solution coverage: 0.652174
solution consistency: 1

--- INTERMEDIATE SOLUTION ---
frequency cutoff: 1
consistency cutoff: 1
Assumptions:

	Raw coverage	Unique coverage	consistency
finacomp	0.608696	0.347826	1
MidtoHighPPC	0.304348	0.0434783	1

Table 12: Intermediate solution fsQCA2

Source: by the author

solution coverage: 0.652174
solution consistency: 1

6.1.9 Robustness Test and Sensitivity Analysis

The consistencies of QCA1 and QCA2 are high which means that the models are valid as they are a measure for how consistently the outcomes are linked to the empirically observed configurations (see Greckhamer et al., 2018). Raising the frequency thresholds of QCA1 and QCA2 to 90% and decreasing it to 70% does not change the configuration solution. Therefore, the outcomes are robust (see Ragin & Fiss, 2017). The overall high values of consistency indicate a high explanatory power of the solutions of QCA1 and QCA2.

6.1.10 Description of Outcomes

This subchapter describes the outcomes of QCA1 and QCA2.

QCA1

The parsimonious solution presents the combination of conditions that are most important and cannot be left out (Fiss, 2011). In QCA1, it is not a combination of different conditions but the presence of one, which is hardware, that results in the absence of values of a high PPC with both raw and unique coverages of 0,8 and a consistency of 0,97. The complex and intermediate solutions consist of a combination of hardware and fragility with the same coverages and consistencies.

Consistency measures how much the respective configuration of conditions is a subset of the outcome (Ragin, 2017). So, 97% of cases where there is membership in the hardware group show the outcome of no high values of the PPC. Put differently, most cases where high levels of peer production occurred were not producing hardware.

The solution coverage measures how many of the cases where the outcome of no high values of the PPC occurs, can be explained by the configuration of conditions present in the respective solution (Ragin, 2017). So, when the parsimonious solution has a solution coverage of 0,8, this means that 80% of the cases where no high values of the PPC occurred can be explained by the absence of hardware being the economic good that is produced.

Raw coverage displays how many of the cases where the outcome occurs are explained by the respective combinations of conditions whereas unique coverage measures the proportion of these cases where the occurrence of the outcome can only be explained by the configuration of conditions at hand (see Ragin 2017). Since in QCA1 raw and unique coverages are identical, in 80% of the cases, the respective configurations are the only combination of conditions that explain the outcome and the configurations of the solutions are part of 80% of the overall sample of cases.

Overall, all three solutions consistently point to hardware and fragility as key factors in explaining the absence of high values of the PPC. Raw coverage (0.8) and unique coverage (0.8) are the same for all three solutions, indicating that the solution configurations consistently explain a substantial portion of cases. The solutions have a high consistency (0.97), which means that the identified conditions predict the outcome of interest reliably, the absence of a high score in the PPC. The parsimonious solution, which includes only hardware, provides a simplified model without compromising consistency, indicating that hardware is the primary driver of the absence of a high value of the PPC, the outcome.

QCA2

The outcome of QCA2 is that the two conditions, the existence of financial compensation (finacomp) and the occurrence of a mid to high value in the PPC (MidtoHighPPC), are each individually associated with the outcome of a success of the project. Each configuration as well as the overall solution consistency are 1, which indicates that the conditions each individually are valid to predicting a success of the project.

With a raw coverage of around 61%, financial compensation is present in successful hardware cases. In around 35% of the cases, it is the only condition that is associated with success. Mid to high scoring in the PPC occurred in roughly 30% of successful hardware projects, whereas it is the only present condition in around 4,4%.

The solution explains 65% of the cases where the outcome, success, is present, which makes it empirically significant. The three different types of solutions (complex, parsimonious and intermediate) give the same results of overall solution coverage, consistency and arrangement of conditions with their respective coverage and consistency values.

6.1.11 Interpretation - Relating Results to Cases and Theory - Patterns and Generalisation

In this subchapter, the outcomes described above are interpreted in the context of this study. QCA1 clearly shows that in the cases where hardware is the good being developed, high scores of the PPC are not achieved. This is in line with chapter 5.3, where it is explained that hardware is not ideal for being peer produced. This allows questioning that approaches the development of hardware in the same way as inherently digital goods. The outcome that if less simplified by the Quine-McCluskey algorithm, the condition of hardware is combined with the condition of fragility holds no additional interpretative value.

QCA2 indicates that both financial compensation and a mid to high score in the PPC each individually predict the outcome of success. The fact that in all three solutions (the complex, parsimonious and intermediate solution) the results are the same, emphasises that it is indeed both conditions standing individually that predict a success of a hardware project.

In more than 60% of the cases of hardware production that are considered a success, there are substantial financial compensations either from the contributory work itself or from the documentation or its physical derivatives. The direction of causal relation logically goes both ways. Contributors that are paid for their work tend to be good at what they contribute, which makes it no surprise that the result then is also good. The other way around, when a successful project draws attention from organisations that start paying for further advancement or adoption of the existing project to incorporate into their venture, is reasonable as well. One prominent example from the software world is the Linux Kernel, which was initially published by Linus Torvalds without being compensated for it under a license which did not guarantee him financial compensation from further economic exploitation. Over time, many major tech companies, such as IBM, Intel or Google, have adopted the Linux Kernel and pay their staff to contribute to the Kernel's further development (The Linux Foundation, 2020). Regardless of the major tech companies' contributions, there still are individuals who self-assign work on contributions that become merged into the main branch.

QCA2's second solution term indivates that around 30% of hardware cases that are considered to be successful have a mid to high score in the PPC. This solution hints at a positive association between the number of people willing to engage substantially in the development of a hardware project and the project becoming a success. This solution term's direction of causal relation also logically works both ways. A successful project draws attention from potential contributors, because they will find their contributions recognised more. A mid to high score in the PPC means that many contributors each contribute considerably, which obviously contributes to the success of a project. This is in line with Spaeth and Niederhöffer's (2020) summary of research on motivations for contributions to peer production.

In accordance with chapter 5.3, interpreting QCA1 and QCA2 together, it becomes clear that often hybrid forms of economic governance regimes occur. In over 60% of the successful hardware cases, the success can be predicted by the financial compensation that a substantial share of contributors received. An explanation for this is that a substantial number of contributions have low granularity, meaning that the sizes of work packages are too big for volunteers to do in their spare time. Even though there are cases where larger contributions are done by sheer volunteers, the overall pattern here is that such projects would be more successful if organisations take part, leading to individuals being paid for their contributory work. Taking into consideration transaction cost already, hardware has lower overall granularity, because its documentation is always just an abstraction. For distributed collaboration, often enough, physical prototypes or parts at least must be shipped, sometimes between peers, making it an exception rather than the norm that peer production of hardware occurs. So, if digital collaboration on hardware development is successful, often this is due to a hybrid form of economic governance, where individual peers collaborate with organisations.

6.2 Literature Review Adding to Findings of QCA1

So far, and especially by QCA1, it has become evident that hardware is less suited to being developed in peer production than intangible goods. Following that, it is now the aim to understand the reason for this difference. Therefore, this subchapter conducts a literature review to see whether previous literature has provided an answer to this.

Defining the Research Focus

- Is there any literature that addresses why peer production of hardware designs is rare?

Searching for Relevant Literature:

- Web of Science (core collection) and Scopus

Searching for Relevant Literature

- Web of Science (core collection) and Scopus
- Search terms: (“Hardware” OR “Manufacturing” OR “Tangible” OR “Physical”) AND ("Peer product*" OR "Mutual coordination")
- Search fields: title and abstract
- Timeframe: all
- Language: all
- Publication Types: peer reviewed articles, reviews
- Subject areas (Scopus)/Web of science categories: all
- Execution Date: 20.09.2024
- Scopus and Web of Science: 126
- After removing doublets: 85
- After reading titles and abstracts: 9
- After reading full texts: 6

Hereinafter, the final sample of the literature review is analysed. Raasch et al. (2009) conduct an explorative study on the institutional and organisational structures of open design for tangible goods. However, their analysis does not extend to evaluating the potential of peer production in hardware development. Similarly, Koch and Tumer (2009, p. 105) briefly mention the possibility of treating early-stage hardware designs as investments within an open design platform. However, this notion is not derived from a broader analysis of distributed hardware development but rather presented as a speculative feature. Furthermore, they do not incorporate decentralised ledger technology (DLT) into their discussion.

Aryan et al. (2011) highlight the disruptive potential of open innovation platforms for physical product development. Nevertheless, they do not examine the practical feasibility of such platforms or the barriers that may hinder their realisation. Balka et al. (2009) argue that hardware owners benefit more from opening software components rather than hardware aspects. They conclude that OS development of tangible products appears feasible but note that, at the time of their study, it was premature to evaluate its scalability. Importantly, they do not consider the role of peer production in hardware development.

Hilgers et al. (2010) reference the concept of peer production and acknowledge the work of Benkler (2002). However, they do not apply his and Coase's (1937) transaction cost analysis to assess the viability of peer production beyond software. Consequently, they assume no fundamental differences in transaction costs between distributed software and hardware development, leading them to conclude that peer production is equally viable for both. This assumption, however, lacks empirical validation specific to hardware. Gerhardt (2020) does not provide an analysis of the dynamics of distributed collaborative hardware development. Similarly, Troxler (2010) focuses on Fab Labs but does not extend his analysis to distributed collaboration in hardware design.

Overall, while the reviewed literature acknowledges various aspects of open and distributed hardware development, the reason for peer production being less suited to hardware then intangible goods is not analysed. Also, significant gaps remain in evaluating the economic, organisational, and technological implications.

6.3 Significance of the Economic Characteristics of the Economic Good Being Produced

The empirical evidence given by the QCA studies supports Benkler's (2002) emphasis on the economic characteristics of the good being produced. To analyse this further, this subchapter uses three basic economic methodologies: transaction costs, marginal costs and network effects.

6.3.1 Transaction Costs

Chapter 2 and 5 have already used the transaction cost approach to distinguish hardware from intangible goods' ability to be peer produced.

6.3.2 Marginal Costs, Prices and the Dogma of (Free) and Open Source

Software consists of digitised information represented by binary digits (bits), whereas hardware is composed of physical atoms, with its documentation serving only as an abstraction rather than a perfect representation of the actual product. Digitised information is a non-rival good with low marginal production costs, as its primary input and output are both forms of information. In contrast, hardware is typically a rival good, as its use is constrained by physical limitations. Additionally, the inputs and outputs of hardware are often not other hardware. In summary, digitised information exhibits low marginal costs, whereas hardware generally incurs high marginal costs (see Benkler, 2006, pp. 35–57).

According to microeconomic theory, prices are optimal when they equal marginal cost[12]. Copying software from one database to another has a near zero marginal cost, which can be part

[12] The precondition therefore is perfect competition, which outside theory almost never occurs.

of the explanation as to why OS digital goods, where the price is zero, are successful. Hardware, on the other hand, has a higher marginal cost and can therefore, according to microeconomic theory at least, legitimately have a price tag. The documentation of hardware is digital but also, as explained in chapter 5, ponderous, because in most substantial use cases for OSHD, the actual physical good needs to be acquired. This is a strong argument for the difference between OSH and open (also meaning free) source software, which seems to not get the appropriate attention, especially in the field of the rather dogmatic community around OSH. What would be optimal instead is to rally for source-available hardware, where economic exploitation is allowed under the condition that the initial inventors get a share of the financial gain that is gained from the physical derivative of the documentation. Native software components of hardware documentation, such as firmware, could still be free and OS. This is explored further in chapter 9.

6.3.3 Network Effects

In the contemporary digital economy, network effects have emerged as a pivotal concept for understanding the success and growth of many platforms, technologies, and collaborative ecosystems. Network effects occur when the value of a product or service increases as more individuals use it (Katz & Shapiro, 1985). This phenomenon creates positive feedback loops that can lead to rapid user adoption, market dominance, and the establishment of significant competitive advantages. From social media platforms like Facebook to digital marketplaces like Amazon and eBay, network effects underpin much of the functionality and scalability of modern technological systems.

At its core, network effects can be classified into direct network effects and indirect network effects. Direct network effects are seen when the utility of a network grows as the number of participants increases, such as in telecommunications or social networking. In contrast, indirect network effects arise when the growth in one side of a platform (e.g. users) enhances the value for another side (e.g. developers), as evident in app ecosystems like those of Android or iOS.

Network effects are a useful analytical tool to understand the dynamics and success of peer production. Attracting a critical mass of participants brings a momentum required for ongoing development. Network effects ensure that as more developers contribute, the utility of the software improves, drawing even more users and contributors into the ecosystem. This virtuous cycle not only enhances the quality of the output but also fosters a collaborative community that drives further participation. For leveraging the forces of peer production for a green growth economy, aiming for hardware development becoming subject to network effects is crucial. It is usually in the beginning of hardware development projects, where the network effects are low and the success of the project depends on the individual motivation of the initial inventor, which one may consider as a gap when the goal is to achieve the leveraging of peer production for a green growth economy. This will be explored further below.

7. Tokenisation and Hybrid Forms of Economic Governance Regimes

The QCA results display clearly that the forces of peer production cannot be leveraged in the development of hardware as done previously in sheer information production. Nevertheless, digital collaboration can realise significant force in the production of hardware documentation for a green growth economy. A hybrid form of economic governance would be necessary therefore, in order to mitigate the partly high transaction and marginal costs which hinder project growth and result in lower network effects. Specifically, a global collaboration in hardware documentation production of individuals and medium- to large-sized firms pool potentially many resources and leverage much force. The larger the individual investment, i.e. the bigger one's organisation is, the more likely it is that one only contributes if participation in the economic exploitation of their invention or its derivatives is assured.

A hybrid form of economic governance regimes is an economic space where individual peers collaborate with firms and optionally parts of the development can be bought from a market. DLTs can provide the necessary institutional infrastructure for the realisation of a hybrid form of economic governance regimes. It is the purpose of this chapter to elaborate on this.

7.1 Distributed Ledger Technologies

DLT represents a paradigm shift in how data is recorded, shared, and managed. At its core, DLT refers to a decentralised database system in which records, often referred to as "ledgers" are maintained across multiple nodes. They are a combination of cryptography, OS software, computer networks and incentive mechanisms. DLTs, also called blockchains, form a consensus about the true state of these ledgers and an intermediating or centralising actor is not needed (Swanston, 2014). DLTs can record any type of digitisable information.

An essential part of double-entry bookkeeping are ledgers, which make them a foundational institutional technology of market capitalism. DLT also enables trustworthy ledgers and they can be viewed as an institutional technology. From a transaction cost perspective, DLTs lower the transaction cost of some economic exchanges. Essentially though, blockchains are a new form of coordinating economic activity (Davidson et al., 2018).

7.2 Tokenisation Enhancing Hybrid Forms of Economic Governance Regimes

In terms of their economic characteristics, hardware repositories, or projects, are not homogenous. For example, in parts of hardware projects, typically CAD files, TCs are comparably higher. Financial compensation through tokenisation can fill the gap of development where transaction costs are high, typically CAD files, and the network effects are low, usually in the beginning of open hardware development. As QCA2 has shown, financial compensation in distributed hardware development projects is a significant factor for success.

The benchmark for the administration of this financial compensation are central foundations dedicated to the administration of one specific project each, as it is how financial compensation of successful OS software development often is organised. Hypothetically, distributed hardware development could also be compensated through foundations. DLTs, however, promise to be a more efficient, effective and scalable solution, which is what this subchapter will elaborate on.

Tokenisation, enabled by DLTs, provides a powerful mechanism for incentivising collaboration in distributed hardware development, also fostering hybrid governance regimes. By assigning digital tokens to contributors, it is possible to recognise and reward contributions in a transparent and decentralised way. Tokens can represent ownership rights, profit shares, or access to specific benefits, which ensures that individuals and firms receive returns on their investments. The investments could be a contribution to the documentation to support current developers to finish the development, or the investments could be purely financial. This creates a strong incentive for organisations and individuals to contribute their resources and expertise. This does not rule out other forms of economic governance regimes. To the contrary, it enables a new kind of development form of open hardware, where different forms of economic governance regimes mutually support each other. Reflecting the different sizes of transaction and marginal costs of hardware and its documentation, its production is optimal when different economic governance regimes occur in one project or product. For example, a firmware could be peer produced, the CAD files contributed by a company and a microchip bought on a market. It is also important to understand that in reality, hardware repositories can only be developed relatively superficially by the "developers". Usually, most subcomponents are sourced from markets. This is true for companies and peer production. So, the question is how deep the development of hardware actually is. In that sense, the market economic governance regime is always present. This is reflected in the fact that OS hardware projects have bills of materials, which list all the goods which are bought from markets. Making early-stage open hardware repositories investment possibilities, capital can support a hardware project until a critical mass is achieved and peer production kicks in. This is another example of how firm and peer production could mutually stimulate each other through tokenisation. One could argue that the finance crowds out some intrinsically motivated peers. However, projects must not be forced to financialise. So, one must not assume the effects of substantial crowding out, especially since the OS hardware space is still relatively small.

Moreover, tokenisation enables fractional ownership, allowing even smaller contributors to participate in and benefit from large-scale projects. Such mechanisms can address the challenge of aligning diverse interests, thereby unlocking the full potential of peer production in hardware development and documentation.

A mechanism that remunerates contributors for down chain economic exploitation of their repositories would soon need to administrate many transactions, including very small ones. Modules of hardware designs which hundreds contributed to can be integrated into other modules which are in turn put into end products. When such end products get sold, manufactured, updated, upgraded, repaired and recycled, it is obvious that the compensation schemes become complex. So, without micropayments and smart contracts, which automatically are conducted at low TCs, it is hard to imagine how such a system would be feasible due to efficiency. Coordination problem in after-manufacturing compensation between manufacturer and repair services and after-manufacturing-services can be solved by digital currency.

With regards to the development of hardware, tokenisation additionally provides trust and incentive structures for ecodesign. Having the crowding out critique in mind, in the use case where a company initiates a project on a digital infrastructure that uses DLT to provide trust, a peer production community would potentially not have to trust the company but the digital infrastructure. If hardware development repositories are tokenised, different events that are downstream the value chains can give remuneration. For example, a digital infrastructure can be set up in such a way that the more the design functions according to ecodesign principles, the more remuneration the initial developers receive. This would give a strong incentive to design ecologically and decouple cash flow growth from resource extraction. One can see here already how well tokenisation can enable green growth. Further, downstream of sales in the value chain, customers can more easily become co-producers by offering their products for resale or accessing the product's repository via the unique identifier on their product. Customers can contribute to further development of the product by suggesting an idea or offering a review of existing ideas. Hence, also downstream a hybrid of different forms of economic governance regimes would occur. The next chapter further explains how tokenisation can facilitate green growth.

8. Synthesis - Leveraging Peer Production for a Green Growth Economy to Transform Into a Golden Age of the ICT Paradigm

This chapter synthesises the previous findings into a generic understanding of an economy within which the forces of peer production can be leveraged for a green growth economy. In order to do so, first, the findings that are essential for the concept are briefly summarised. With that basis, the generic understanding of a green growth economy within which peer production has a major role is derived. Moreover, a standard value chain of such an economy is differentiated according to significant changes in economic characteristics, i.e. marginal and transaction costs. Each phase along the value chain is described in more detail, and economic actions, as well as transaction and marginal costs are elaborated on.

Next, Benkler's (2002) method of explaining the occurrence of economic governance regimes according to the respective transaction costs is adopted to predict the occurrence of economic governance regimes at each phase of the value chain. Furthermore, there is a distinction made between the actual economy and the infrastructure that is a precondition for the former to develop; specifically, a physical and a digital infrastructure upon which a green growth economy, enriched by peer production, could emerge. Based on that, one way of a potential realisation of such a digital infrastructure is presented in more detail, which is then compared to similar real concepts. Finally, chapter 8 returns to the theoretic framework. The previous synthesising outcomes are taken up and elaborated on through the lens of TEPS. This includes developing approaches of how a transformation towards a green growth economy could actually take place.

8.1 Brief Consolidation of Findings Essential for a Green Growth Economy in the ICT Paradigm

Chapter 3 explained that the TEPS framework's golden age of the ICT paradigm is to be achieved in green growth. An note-worthy characteristic of the ICT paradigm is the force that online collaboration of masses can enfold. One can see this in examples such as Wikipedia or free software development, as mentioned before. Similar to these, the idea of leveraging forces of peer production for green growth is that large numbers of peers contribute to open designs of hardware, and manufacture, repair, update and recycle as much as possible themselves or locally. This is an approach for a golden age of the ICT paradigm.

A key challenge is how hardware developers, whether individuals or firms, could be incentivised to comply with ecodesign. In this context, as laid out in chapter 4, the ESPR shapes the regulatory framework in such a way that successively ecodesign will become the norm. At the core of this transformation are DPPs, which will be required for almost all physical products on the EU market. These DPPs will entail information about a product's life cycle, including its materials, components, manufacturing processes, and recycling or disposal methods. Previous after-manufacturing and recycling phases of individual modules and materials will be included. In other words, the whole physical value chain will be recorded. The rationale thereby is to enforce ecodesign by raising the standards and ensuring that violation of such is transparent through the digitalisation via the DPPs. Moreover, by checking the DPP, customers will be informed about the degree to which a product abides to ecodesign.

Chapter 5 elaborates on peer production in more detail, starting with a definition and then portraying the relevance of governance in it as well as exploring the peer production of hardware. Specifically, chapter 5 defined peer production from a transaction cost perspective, classifying it as an economic governance regime besides markets and firms. Chapter 6 conducted QCA1 which showed that hardware is empirically a factor that hinders high levels of peer production. QCA2 gave the result that hardware projects are predictively successful when they get financial compensation and have mid to high levels of peer production. Chapter 7 explored how tokenisation can enhance hybrid forms of economic governance regimes and incentivise compliance with ecodesign.

8.2 Deriving a Generic Understanding of a Green Growth Economy that Leverages Forces of Peer Production

Having summarised basic findings so far, these findings are taken to derive a generic understanding of a GGEPP. Peer producers of hardware would at least partly get motivated joining a development by experiencing potential for optimisation with regards to products they use themselves. So, their motivation to contribute is to simply create a better product. As a business turnover is a function of its sales' quantity, it is also positively connected to resource extraction and processing. So, the profit is higher the more often a product breaks and hence, currently, the incentive structure is the opposite of what it needs to be in order for developers to design ecologically. With tokenisation however, product developers could be incentivised to design ecologically. This can be done by either rewarding behaviour that complies with ecodesign or sanctioning those who do not comply with ecodesign.

Synthesising all this means deriving a value chain that accounts for the aforementioned factors. Hereby, the development of hardware occurs in hybrid forms of economic governance regimes, enhanced by tokenisation. For example, version-controlled repositories are linked to a blockchain, where each contribution is saved on ledgers. This is the basis for later remuneration of the hardware developers, based on the performance of their designs and its derivatives down chain from the development phase. This would form a global data commons of hardware documentation or designs that comply with ecodesign, which is very attractive for consumers. This is because these products would be long-lasting, repairable, and transparent in their level of eco performance and compliance. A DPP would then not only contain material composition and some more information about the product, but would also be a design passport which simply links to the original repository where the hardware documentation is stored.

A generic digital network's architecture that hosts the digital commons of hardware documentation repositories (designs) is to be federated. A federated software architecture is one where there is not one central entity hosting the software but multiple instances which make it more reliable due to the lack of a single point of failure. A common use case for a federated system is the Simple Mail Transfer Protocol (SMTP), where users sign up with client providers such as gmail.com or gmx.de. If, for example, the gmx.de-servers go offline, all other providers and their users can still send emails among each other. The same would be true for the digital network upon which the digital commons of hardware designs are hosted. For example, each city or region could initiate an instance for local users to sign up on.

Following (Berg et al., 2022), there is a positive connection between source availability and circularity performance. This is why the network's precondition for all contributions should be that their source stays available, which does not rule out legal regimes where contributors participate in the economic exploitation of the designs or its physical derivatives. In addition, chapter 6.3.2 has explained that the replication of digitised information has near zero marginal cost and that in such a case, the microeconomic suggestion is a near zero price of the information, meaning that the source is available for free.

Since there are different regulations and market dynamics in different areas around the world, regional manufacturing experts can take the hardware documentation from the global database and organise their productisation and manufacturing for their respective jurisdiction. To sell these products, existing e-commerce stores are utilised. When customers then buy the products, have them repaired, upgraded, updated or recycled, the initial developers get a share of the price from the respective phase. This price is optional for the developers to demand as part of their legal agreement at the repository level.

8.3 Identifying a Suitable Economic Governance Arrangement along the Value Chain of a Green Growth Economy that Leverages the Forces of Peer Production

To answer the question of which economic governance is suitable for different phases of a CE's value chain (RQ2), the value chain must be divided into different phases. The methodology used therefore is that a new phase begins when the economic characteristics as well as the suitable economic governance change. The following explains the value chain from the beginning to the end and identifies significant changes in the economic characteristics in terms of transaction and marginal costs.

The focus of this study has been the decentralisation of the development phase of hardware. However, decentralisation is feasible later in the value chain of physical goods. A proprietary benchmark in the textiles branch is the project Garment to Garment, based in Hong Kong. It recycles post-consumer garments into new ones in a production line sized to fit into a container. On the OS side, the Open Lab Starter Kit project benchmarks the decentralisation of production machinery. These projects indicate the decentralisation of production processes down chain from the development of products. It is an overall goal of the ESPR to foster decentralisation in post-consumer phases of value chains. The ESPR prescribes that repairing and recycling will be done technically and in a legally feasible way by decentral actors, and not only the initial manufacturing company, as it is often the case when preventing decentralisation.

It is not suggested that there would ever be a total adoption of that value chain. A more realistic option is a varying hybrid form of different types of chains, depending on the type of products one looks at. Nevertheless, for analytical purposes it is necessary to construct a "pure" form of the chosen value chain.

8.3.1 Description and Analysis of Each Phase

This study divides the value chain of OSH production into five sections. The main reason for the differentiation into five phases is that each of the phases differs from the previous or following in its marginal and/or transaction cost characteristics, leading to different occurrences of different economic governance regimes. The following elaborates on this by describing the economic actions and transactions as well as their marginal and transaction costs through the whole value chain. This is conducted in a "sterile" way, meaning that it only looks at the production processes themselves and - for now - ignores the status quo as well as how realistic different economic governance regimes appear in the present.

In the beginning of each section, representing a phase of the value chain, the economic action and the transactions are described. It is not claimed that if implemented it could only be this way. But they present at least one major possible way of leveraging the power of peer production for a green growth economy. Following the description, a derivation of the respective transaction and marginal costs is conducted. The marginal costs are categorised as high, medium or low, whereas transaction costs are scaled from 1 (low) to 4 (high).

1. Invention and Development

Developing hardware products is phase one of the value chain of an economy that leverages peer production for green growth. It is where new products are developed and documented by either an individual or a potentially geographically dislocated group of people, i.e. an organisation or a firm. The new designs can be adapted forks of existing designs. The actual transaction, marking the end of phase 1 is the publication of a hardware documentation to a digital network. The core previous action before the transaction is the development of a digital documentation of a new physical artefact. Its development can be done digitally with computer aided design (CAD). Yet because the product in the end is physical, one can assume that at least one prototype is being manufactured in the development process. The norm is that several subcomponents are sourced from markets, which are listed in the bill of materials (BOM).

There are a multitude of different economic actions at phase one, but the basic one is the following:

Generic Showcase 1

An inventor has an idea for a physical artefact and goes to a local Fab(rication) Laboratory, microfactory, Open Lab(oratory) or open workshop (Fab Lab in the following) to realise the idea into a prototype. The local Fab Lab helps by providing machinery and the skillset to use the machines and document the prototype properly for publishing it to a global network. As in OS software development, forking and improving existing repositories is common (see generic showcase 2). So, the Fab Lab is likely to integrate existing modules from the network or markets to develop the prototype. If the idea was a 3D printer, the Fab Lab would not reinvent a stepper motor, but integrate an existing one. The stepper motor could be bought from a market or, if available, integrated as a module from the digital network. Of course, the license of the existing module from the network would need to fit.

The inventor now needs to choose one of the licensing models the digital network offers, ranging from copyleft to permissive and commercial to non-commercial options. The Fab Lab hereby assists the inventor. The inventor chooses a commercial and strong copyleft licensing model. This means that the hardware documentation is allowed for commercial usage, but only if the inventor is remunerated. To strengthen the inventor's claims, the inventor can also patent the invention. Now the prototype has been built and the documentation is ready. The Fab Lab and the inventor agree that the Fab Lab's effort is worth 50% of the overall value of the invention. Next, the inventor creates an account on the digital network. The Fab Lab already has an account and uploads the hardware documentation to the dashboard of its digital network. Hereby a repository is created. The Fab Lab makes the inventor a co-owner with 50% of the repository. Following up, the Fab Lab and the inventor publish the documentation to the digital network. Hereby, the repository is hashed to prevent falsification. The hash as well as information on the owners and their share of the overall value of the OSHD is put into a design passport which is automatically added to the repository.

Generic Showcase 2

Another generic showcase for phase 1 is when a design is distributed between different nodes of the digital network and these nodes collaborate via digital tools. Mostly, this is when users suggest contributions to existing designs. This can also be done by customers themselves. For example, a customer has bought a vacuum cleaner, which is based on a repository on the digital network, from a regional e-commerce store. The customer comes up with an idea on how the vacuum cleaner could be improved. The customer goes to their local Fab Lab and gets help to realise a physical prototype of the idea. The Fab Lab could scan the original QR code of the physical vacuum cleaner to get access to the DPP and the original repository the hardware documentation from the vacuum cleaner is stored in. The Fab Lab now forks the repository to the dashboard on its local instance of the digital federated network. Here it adapts the hardware documentation to the customer's ideas. The Fab Lab and the customer agree that the value addition of their improvement is split equally between them and that their value addition to the original repository of the vacuum cleaner is 20%. The Fab Lab edits this information on its local instance’s dashboard. They also agree with the license of the original repository which is commercial and copyleft. Now the Fab Lab opens a merge request to the owners of the original repository. The owners of the original repository receive a notification about the merge request with the changed documentation and the conditions under which the merge request is done. The owners like the improvement. However, they do not value it 120% compared to the original design, but think it is only 110%. The owners suggest this to the Fab Lab. The Fab Lab and the customer agree and cancel the original merge request and initiate a new one with the same hardware documentation but with a 10% value addition. The original owners confirm the new merge request. The hardware of the main repository of the vacuum cleaner is becoming the one from the merge request. The new ownership shares are listed in the design passport:

- Original owners: 100%/110%
- Fab Lab: 5%/110%

- Customer: 5%/110%

This distribution of shares determines the governance in decision making as well as remuneration allocation.

Transaction costs at phase 1

- Information generation for the inventor on the local Fab Lab that can assist in prototyping and documenting the invention.
- Coordination cost with the Fab Lab: scheduling meetings
- Sourcing hardware subcomponents for the prototype. This cost is highly considerable. For a prototype with the complexity of a FDM desktop 3D printer, a total number of in between 50 and 100 parts is realistic. Around 40 hours of working time for this process alone is realistic in a country like Germany, even though many of these parts are common in Fab Labs.
- Bargaining with the Fab Lab and other product owners that own repositories integrated into the invention.
- Enforcement and policing cost.
- Shipping of physical derivatives of OSHD.

Compared with inventing and designing products in the linear economy, the transaction costs at this stage vary drastically, depending on the type of invention. Generally, the more complex an invention is, the more transaction costs the process will have. What is different with such a digital federated network or infrastructure is that the transaction costs can also be very low. This is because the digital federated network lowers the threshold of contribution to inventing and designing products. Therefore, the overall transaction costs of phase 1 are considered of class 1 (low), 2, 3 and 4 (high).

The marginal costs at phase 1

Developing an invention is by definition always novel. The invention of a certain product cannot happen twice. However, if all inventions were grouped into a group of inventions, one could assess how much an additional unit of the good invention costs. Then it becomes clear that prototyping and documentation require much manual effort. Although the software that supports the process for creating documentation gets better and cheaper, the degree of automation is comparably low. Therefore, the marginal costs at phase 1 are high. Nevertheless, in general one can say that taking into account forking and improving existing hardware documentation, the less the degree of novelty is, the lower the marginal costs are. It is worth mentioning that there are attempts to automatise the development of inventions with artificial intelligence (AI). A radical approach of this is taken by the company Hyperganic, which uses AI for developing new rocket engines. To this date it is not clear when, or if, this technology will be ready (Blakey-Milner et al., 2021, p. 18). If it would be ready at some point, it could have the potential to reduce the marginal costs in phase 1. Because this technology is still premature at this point, it is not taken into account in this study.

2. Multiplication of Hardware Documentation Through a Federated Network - A Global Digital Commons

The distribution of hardware documentation among the global digital federated network of nodes or instances makes up for a global digital commons and is phase 2 of the value chain. The core transaction in phase 2 is the digital duplication of the hardware documentation. In phase 1, digital duplication of hardware documentation also occurs when designers fork repositories. In distinction from phase 1, digital duplication in phase 2 is done for the purpose of either marketing, manufacturing, user-applications, after-manufacturing or material recovery workflows.

In order to analyse phase 2, its technological underpinning is explained in more detail. The software architecture of the digital federated network in the backend is federated. Here, federated means that there are several interconnected servers (nodes) that communicate with each other, but are independent. All nodes of the network together form a federation. This distinguishes the network from conventional platforms such as Wikifactory.com, which have central architectures in their backend. An instance of the network does not automatically store a complete copy of the whole hardware documentation that is published to the network federation. Publishing a hardware documentation to the network federation primarily means that it can be found by other nodes and its users. An exception is the design passport, which is stored on a blockchain (DLT). Each node stores a complete copy of the ledger. The rest of the hardware documentation is transferred to another node, when a user of that other node forks it.

Generic Showcase 1

A manufacturer in Paris wants to manufacture a product of category X. The manufacturer registers on the Paris network instance. On the dashboard, the manufacturer searches for products of category X. A list of all hardware documentation matching with category X is displayed. The manufacturer chooses hardware documentation Y from the list and clicks on "fork". Now hardware documentation Y is duplicated to the Fab City Paris instance by copying it into a new private repository on the Paris instance that is privately accessible for the manufacturer X. Manufacturer X can now check out the details of hardware documentation Y and assess whether to manufacture it.

Generic Showcase 2

Generic showcase 2, essentially forking repositories to one's own repository, is mostly an automated digital process. Finding and selecting OSHD has low marginal costs compared to centralised linear production. Overall, generic showcase 2 therefore has low marginal costs.

Transaction Cost

Transaction costs at phase 3 are searching costs. Compared with transaction costs in other phases, these are to be considered 1 and 2.

Marginal Costs

The essential transaction of copying digital designs from one account to another has near zero marginal cost.

3a. Regional E-Commerce: Marketing and Sales

Phase 3 of the value chain of distributed production is regional e-commerce which entails sales, distribution and marketing. It essentially encompasses the organisation of the offering and the purchase of hardware documentation as products in e-commerce shops and the compensation of designers according to the design passport and providers of the network.

The core transaction in phase 3 is the purchase of a hardware documentation-based product in an e-commerce store.

Generic Showcase 1

An e-commerce store wants to add a hardware documentation as a product of category X to its product portfolio. The store has already technically managed to fetch hardware documentation from the global digital federated network into the pool of products offered on the store. The hardware documentation of category X under commercial licenses in the global digital federated network is searched for on the dashboard. A list of matching hardware documentation is displayed and the shop forks some of them to its own private repository on the local instance. Before the store can offer a hardware documentation as a product, it needs to find local manufacturers or microfactories that want to manufacture the products according to the hardware documentation and its licensing conditions. The store contacts both local manufacturers who are already registered on the local network's instance, as well as some who are not yet registered. For the manufacturers that are already registered on the network, the shop only provides a link to the original repositories of the hardware documentation. For those yet registered, the shop can either download the hardware documentation and give access to it via an external tool of its choice or the store can send links to the repository and information on the need to register to access the full hardware documentation on the network. Now the manufacturers assess whether they want to manufacture according to the hardware documentation based on quotes from the shop. The shop and the manufacturer now negotiate the conditions under which they would sell certain products. With the conditions negotiated and agreed, the shop offers the negotiated hardware documentation as products on the shop. The negotiated conditions with the manufacturer together with the conditions in the hardware documentation determine the price for which the product is to be offered.

Generic Showcase 2

Generic showcase 2 entails an e-commerce shop owner who manages compensation. In this showcase, an e-commerce shop owner X offers hardware documentation as products from the shop network. Hereby, X had a turnover of 10,000 € in March. Now manufacturers, designers and others have claims on that turnover for which they need to be compensated. With a growing number of claimants in regions with different currencies and payment systems, the effort to do all these transactions would soon become too laborious. Therefore, the network offers managing transactions via tokens live. The compensation via Fiat money is done in an accumulated way monthly.

Generic Showcase 3

Generic showcase 3 is about purchasing a hardware documentation-based product on an e-commerce shop. Customer X wants to buy a product of category Y and goes to a regional e-commerce platform. Previously, this e-commerce platform was connected with the global digital commons of hardware documentations from the network via the network's API. The e-commerce platform negotiated prices with local manufacturers and is now able to offer some category Y products from the network's digital hardware documentation commons. Customer X starts a search on the e-commerce platform and finds matching products, decides for one of those from the network, and purchases it in Fiat money.

Transaction Costs at Phase 3a.

The types of transaction costs at phase 3 are to be differentiated between customers (generic showcase 3) and providers of e-commerce stores (generic showcase 1 and 2). In generic showcase 3, there are mainly searching costs. In generic showcase 1 and 2, the types of transaction costs are searching costs, negotiation costs, legal and technical assessment costs. All of these costs can be considered comparably medium to high, which classifies them as 3 and 4.

Marginal Costs at Phase 3a.

Once a manufacturer and an e-commerce shop provider have agreed upon the selling conditions, the marginal costs of selling products at phase 3a. are low. It is assumed that the process of adding new products to an e-commerce store is, at least in the beginning of the network, not automated. This includes negotiation and setting up certain technical arrangements. Therefore, the marginal costs are medium.

3b. Replication of Physical Object (Manufacturing), After-manufacturing (Use, Update, Upgrade, Repair, Adaption) and Separation into Modules Or Homogenous Material Stacks for Material Recovery

Phase 3b. encompasses manufacturing and after-manufacturing, based on hardware documentation from the FCOS. The core transaction in manufacturing is the manufacturing of a physical object. The main transactions in after-manufacturing are updating, repairing and adapting physical products. In the materials acquisition, physical products are separated into modules or homogenous material stacks for recycling. At this stage, designers are to be rewarded when the products they have designed can be well separated. One option is that the designers receive a share of the financial turnover in the materials phase. The reward does not necessarily need to be financial, but can consist of user feedback, i.e. reviews. When the materials are integrated in the manufacturing of new products, the DPPs will include information about the developers who designed the product, which integrated materials from previous production cycles. Based on that, it is possible that those previous designers receive remuneration from sales of the product in later production cycles. This makes sense because the fact that the materials are used again is proof that the product has been designed in accordance with ecodesign principles. It is also possible that there are tokens to be generated for when designs turn out to be of high quality in terms of ecodesign principles. Such token generation may be triggered as a result of the sum of some kind of user review.

Showcase 1

Showcase 1 is a manufacturer (X) who manufactures a product. Here, X receives a manufacturing order via the network (email, dashboard,…) for product Y, triggered by the event of a purchase of a respective product on an e-commerce store. Because X has previously agreed to take manufacturing orders of Y from the e-commerce store, X is legally obliged to take the manufacturing order. X now manufactures[13] Y and notifies the customer to pick it up[14]. Several other manufacturing showcases are possible, but this is a standard one, as far as can be told now.

X receives financial compensation for the action via the financial transaction tool of the network according to X's agreement with the e-commerce store.

Showcase 2

Showcase 2 is a customer (C) who gets a mechanical update on a product. C purchased a product from a network's regional e-commerce store. Now C has become aware that there is documentation for a mechanical update available on the network. C scans the product's DPP and gets the information that manufacturer M has manufactured the product. C contacts M to request the mechanical update. M checks the documentation of the mechanical update, which includes the licence. The documentation of the mechanical update is published under a commercial licence and requires M to give the documentation owners a share of 10% based on the documentation of the mechanical update. M agrees with the terms and decides to publish the mechanical update, based on the hardware documentation from the network. M publishes the offer, based on the hardware documentation update, to the network page. C purchases the offer and pays via the network's payment tool.

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[13] X could also have manufactured Y in advance of receiving a manufacturing order.
[14] In the long run, there are supposed to be manufacturers in every neighbourhood, which is why user journey one assumes that the manufacturer is located closely to the customer.

Automatically, the designers of the update receive a 10% share of the price. C now has a conversation with M on when to bring the product to the manufacturer. They agree on a time, and then M performs the mechanical update. Afterwards C picks up the updated product.

Showcase 3

Showcase 3 is a user giving feedback on a product's quality in terms of the after-manufacturing workflows. A user bought a product from an e-commerce store. The product was shipped to the user, who looked up the product's manufacturer. Now the product's firmware is outdated and the user wants an update. To learn more about the product, the user uses a mobile phone to scan the product's QR code. Automatically, a webpage on the standard browser opens and displays the product's DPP. Here, the user sees which manufacturer has manufactured the product and can also click on a link which leads to the public page of the manufacturer on the network. The user now registers on the network and contacts the manufacturer, asking for a firmware update. The manufacturer receives a notification, reads the message from the user and starts looking for a firmware update for the product on the original repository from which the original product was manufactured. The manufacturer found the original process in the network's back office page. The manufacturer calculates how much the customer would be charged for the update, based on how much the repository owners demand. The repository owners demand 30% of the price that a manufacturer receives for doing the firmware update, which is too much for the manufacturer. The manufacturer declines the customer's request. The customer gives a negative review of the firmware's repository on the network.

Showcase 4

Showcase 4 is a product being disassembled into modules and the modules being offered for local distributed manufacturing processes. Manufacturer X offers to buy back network products for a certain price from customers on the shop front end and in an offers and needs matching UI for distributed manufacturing processes. X does this with the intention of disassembling the network products into modules and reusing them for X's own manufacturing, or X can offer them for distributed manufacturing processes.

Showcase 5

Showcase 5 is a product being disassembled into homogenous material stacks and being offered for local distributed manufacturing processes. A product that had been purchased on the network is now broken and cannot be repaired. It cannot be disassembled into modules. The customer therefore brings it to the public waste disposal Y. Y scans the material passport on the product and sees the list of different materials that the product consists of. Now Y disassembles the product into separate homogeneous material stacks. These material stacks are offered on the network for local manufacturing.

Showcase 6

Showcase 6 is a customer reviewing a product's quality in terms of circular economic design principles. A customer finds out that a screw was missing on their cargo bike, which was ordered from a shop connected to the network. The customer scans the QR code on the product with a smartphone and accesses the product's DPP, which includes information on the manufacturers involved in manufacturing the product. There is a link to each manufacturer's profile page on the network. The customer goes to the profile page of one of the manufacturers who was responsible for the screw and mentions this lack of quality in the review section of the manufacturer's public profile.

Transaction Costs at Phase 3b.

At phase 3b., the following types of transaction costs are present: negotiation costs, transportation costs and coordination costs. These transaction costs are significant. Therefore, manufacturing and after-manufacturing (phase 3b.) have high transaction costs. Materials acquisition is subject to storage and transportation costs. Transporting products at their end of life to public waste disposal is a relevant transaction cost. In addition, materials and modules may rest on stock for quite some time before they get sold and are remanufactured. So, storage costs are significant. Reviewing, as described in showcase 3, is comparably fast and simple to do. However, all in all, transaction costs at phase 5 are considered to be of scales of 2, 3 and 4.

Marginal Costs at Phase 3b.

For both manufacturing and after-manufacturing, production of an additional unit has high costs. Distributed manufacturing and after-manufacturing are subject to economies of scope so the scales do not rise to a level at which the marginal costs would be significantly lower. Phase 3b. is expected to have lower scales per economic actor, which is why the marginal costs will be high. The economic action in phase 3b. involves significant amounts of physical labour, which is why it cannot be automised to sheer moving of bits. Therefore, phase 3b. has high marginal costs.

8.3.2 Predicting Markets, Organisations or Peer Production Along the Value Chain

To begin with, this chapter adapts Benkler's (2002) method to the context of this study. As described in the methodology chapter, each of the three phases of the value chain of distributed production is analysed separately.

The three different types of economic governance regimes and their respective transaction costs, laid out earlier, can be applied to the three phases of a green growth economy's value chain. A new phase begins when the transaction or marginal costs change drastically. This is presented in the table 12.

	Transaction costs 4 = High; 1 = Low	Marginal Cost High / Medium / low	Economic governance regime
1. Invention and Development			
2. Multiplication of hardware documentation			
3.a Regional E-Commerce: Marketing and Sales			
3.b Manufacturing, after-manufacturing and materials recovery			

Table 13: Deriving appropriate economic governance regimes from transaction costs along the phases of a GGEPP value chain

Source: by the author

Now, the adapted method of Benkler (2002) is implemented to predict the occurrence of the economic governance regimes along the value chain of a GGEPP. Therefore, the resulting transaction and marginal costs from the previous subchapter are inserted into the following chart.

	Transaction costs 4 = High; 1 = Low	Marginal Cost High / Medium / low	Economic governance regime
1. Invention and Development	4, 3, 2, 1	High	Firms/Organisations, Markets, peer production
2. Multiplication of hardware documentation	2, 1	Low	Firms/Organisations, peer production
3.a Regional E-Commerce: Marketing and Sales	4, 3	Low	Firms, markets
3.b Manufacturing, after-manufacturing and materials recovery	4, 3, 2	High, Medium	Firms, markets

Table 14: Application of derivation of appropriate economic governance regimes from transaction costs along phases of a GGEPP value chain

Source: by the author

8.4 Distinguishing Capital- and Commons-Oriented Trajectories

The developmental path of any TEPS is not predetermined. The ICT paradigm could further unfold without leveraging the forces of peer production for a green growth economy. In the case that the forces are being leveraged, there are still major differences possible. Essentially, adapting Kostakis and Bauwens (2014), there could be a scenario in which the backend server ownership structures are highly centralised and owned by private capital-oriented actors. Amazon, for example, could build private decentralised microfactories where the partial production of parts sold on Amazon occurs, as well as parts of the later phases of the value chain. Here, peer production could play an empowering role in the frontend as it does today for Facebook, for example. For customers, the showcases could similarly be applied in both trajectories. However, the effect on societal well-being may be drastically different, because capital and power would accumulate strongly when the means of production are centrally owned.

In the scenario where microfactories or Fab Labs are locally owned, the surplus generation of exchange value would be decentralised and more actors would profit. Additionally, there is a fiscal argument to be made. In a capital-oriented trajectory, the tax base of local governments would erode to the degree that the owners of the digital and physical infrastructure are located abroad. Additionally, when a capital-oriented actor owns much of the infrastructure and determines also the incentive structure set by tokenisation, the actor could have the power to change the system in a way that the incentives are no longer pointing in the direction of ecodesign. In sum, it is a vital interest of the state to make sure that the trajectory moves in a more commons-oriented direction.

8.5 Fab City OS as a Commons-Oriented Way to Implement a Digital Infrastructure for Leveraging Forces of Peer Production in the Development of Hardware for a Green Growth Economy

Chapter 8.2 introduces the Fab City Operating System (Fab City OS) as one way to implement the digital federal network explored above. The author of this study was involved in the development of the Fab City OS in a senior role. The learnings from this role influenced the understanding upon which this study evolved. This study also influenced the development of the Fab City OS (FCOS). At the core of the EU-funded project 'INTERFACER'[15] is an attempt to tackle the issue of high transaction costs of digital collaboration in the production of hardware by developing a prototype of a common digital infrastructure (ecosystem) for the global Fab City

[15] https://www.interfacerproject.eu/

Initiative which it calls 'Fab City OS'. The prototype is online[16] at the time of writing. FCOS aims at making processes across all stages of the value chain of distributed production more efficient and competitive compared to linear production. FCOS is to be understood not as a product on a market but as a digital infrastructure for a distributed economy, or ecosystem, in line with the Fab City[17] idea. Fab City is a global network comprising over 40 cities, regions and two countries (Bhutan and Georgia). These locations have joined forces to implement the concept of designing globally and manufacturing locally. This means that hardware documentation is designed in a collaborative and distributed way globally to enable a local circular economy that has access to products that adhere to ecodesign principles. FCOS originated from the Fab Lab network and aims to scale the dynamics of a Fab Lab to the city level. Key to leveraging forces of peer production for green growth, FCOS enables hybrid forms of economic governance regimes in the form of firms, markets and peer production.

FCOS is an OS software stack that enables its users to participate in distributed production more efficiently. It builds interfaces between and combines different existing OS software solutions such as FreeCAD[18], Zenroom[19], Reflow OS[20] or MoVeDo[21]. Hereby, it aims to stand on the shoulders of giants, which means that it builds upon previous OS work. It is this OS approach which makes this high ambition realistic despite its small number of resources compared to large tech-corporations.

On its frontend, FCOS supports user-group specific workflows with specific user interfaces. An essential one of these interfaces is a browser-based page for product designers. It can be compared to Wikimedia, the software behind Wikipedia. As Wikimedia makes distributed production of encyclopaedia articles efficient, the FCOS user interface for designers makes distributed production of hardware documentation (HD) efficient. The user interface supports the

[16] https://interfacer.dyne.org/en
[17] www.fab.city
[18] https://github.com/FreeCAD/FreeCAD
[19] https://github.com/dyne/Zenroom
[20] https://reflowproject.eu/knowledge-hub/reflow-os-graphical-interfaces/
[21] https://github.com/movedo

users in creating a standardised HD file which entails information on who has contributed what to the design (cryptographic design passport), everything needed to manufacture a physical product according to the design (build instruction, BOM, CAM files etc.) and exemplary pictures for e-commerce stores. The pictures can be channelled into e-commerce stores such as Otto.de or Amazon.com.

When a customer buys the displayed product, designers get a share of the price according to their individual contribution stored on the design passport and FCOS sends manufacturing information to local manufacturing capacities so the product is manufactured as close as possible to the customer. In the manufacturing process, the core technology - an adaption of Reflow OS build on Zenroom (Roio, Ibrisevic & D'Intino, 2021) - extends the design passport with information on the manufacturing process, making up for a cryptographic material passport that can be accessed via a unique identifier on the physical product such as a RFID chip or QR code. As far as the ESPR details are released, the FCOS DPP complies with ESPR requirements.

Along the life cycle of the physical product, when it gets repaired, adapted or disassembled into modules or homogenous material stacks for recycling, the product's performance in terms of circular economic design principles is revealed. Due to the design/material passport, this performance can be linked to the responsible designers. This raises the potential to reward or sanction product designers for their circular economic design performance. The business models of product designers could potentially decouple from the quantity of sales and smaller firms could participate in global value chains without relying on intermediaries imposing their business logic upon them.

The backend of the FCOS consists of a federated software architecture. This means that it is not hosted and maintained on one single server owned by one organisation; instead, each Fab City can be a sovereign node of the network by hosting FCOS on its own server to ensure digital sovereignty (see Bria, 2017). However, this does not compromise interoperability and likelihood of global exchange on HD between each node of FCOS.

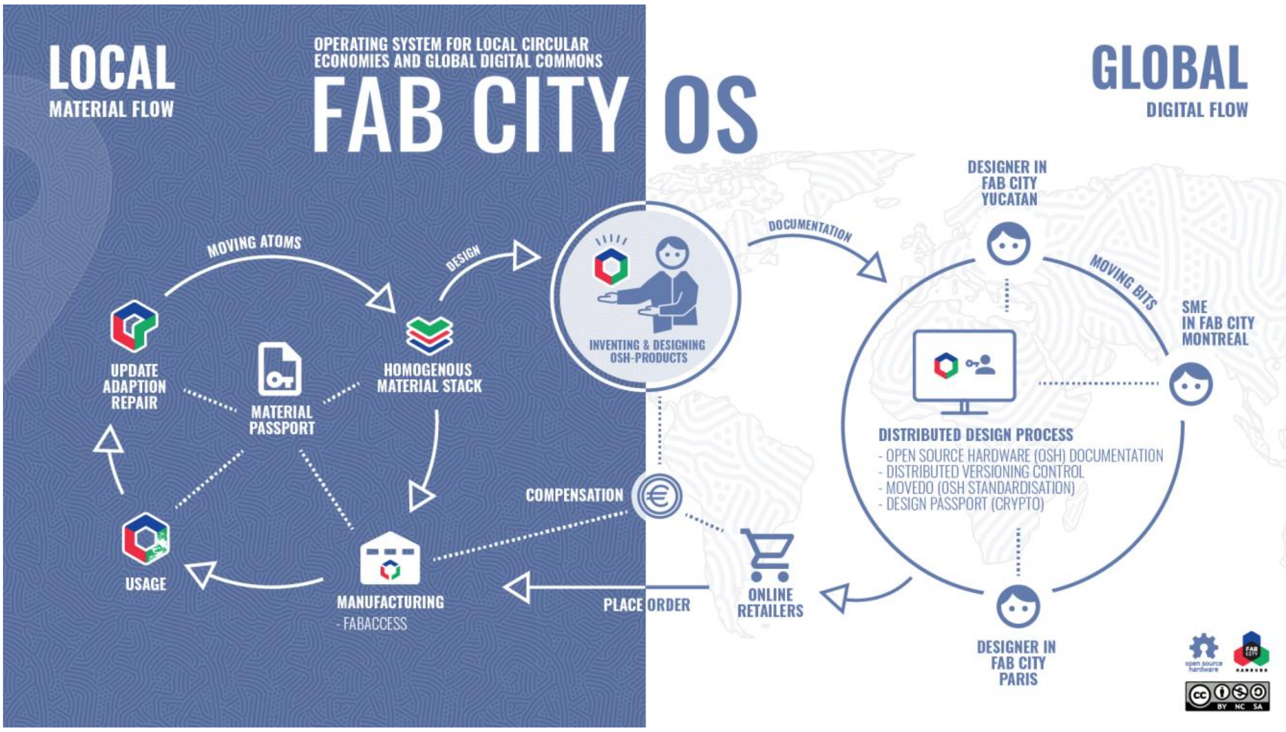

Figure 3: Infographic on the value chain of Fab City OS
Source: Fab City Hamburg e.V., 2021

One of the most common critiques on an idea such as FCOS is that open hardware designs lead to intellectual property theft. But DPPs enable identifying counterfeits immediately at customs or by commerce or end-users. Legally, an optimal system would leave the choice about whether the invention is patented to the developer. Patenting does not rule out openness in the sense of transparency of the source repository. If the HD or its physical derivative is patented, in order to be marketed on FCOS, the source files would have to be available to the public. This is why a green growth economy that leverages the potential of peer production would not be described as purely open source, but rather source available.

8.6 Validating Conceptual Originality Through a Literature Review

As the concept of an infrastructure for an economy that leverages the forces of peer production for green growth has been laid out in the previous chapter, this chapter conducts a literature review and cross-reference-based search for similar concepts.

Defining the Research Focus
- How close does literature such as open innovation for a CE come to the concept developed in this study?

Searching for Relevant Literature
- Web of Science (core collection) and Scopus - Search terms: (“Circular econom*” OR “Ecodesign) AND “Distribut*” OR “Open Source” OR “Source Available” OR “Commons” OR “Open Innovation*” AND “Digital Market*” OR “Digital Infrastructure*” OR “Product Passport*” OR “Material Passport*” OR “Design Passport*” OR “Digital Twin*” OR “Blockchain” OR “DLT*” OR “Distributed Ledger Technolog*” - Search fields: title and abstract - Timeframe: all - Language: all - Publication Types: peer reviewed articles, reviews - Subject areas (Scopus)/Web of science categories: all - Execution Date: 30.08.2024 - Scopus and Web of Science: 75 - Adding hand-selected: 77 - After removing doublets: 49 - After reading titles and abstracts: 9 - After reading full articles: 7

Aryan et al. (2021) report that it is common for users of businesses originating in makerspaces to complain about their lack of compensation. The researchers name microfinancing of maker innovations as a subject of future study. Hence, this study, especially QCA2, gets further justification, but Aryan et al. (2021) have not come up with a concept of how to compensate makers for their innovations. Teisserenc & Sepasgozar (2021) list a few similar aspects to the concept developed in this study, but do not develop them in depth. Mathews et al. (2017) develop the vision of using blockchain and cryptocurrency for designing BIM (construction) collaboratively, but do not go further into the direction of a concept such as FCOS. Hansen and Howard (2013) claim that OSH could be as significant as OS software in terms of impact, if there would be an appropriate platform with efficient tools. However, they do not mention remuneration of developers and purely approach this from an engineering perspective, not from an economic one. Teisserenc and Sepasgozar (2021) also focus on the construction industry and emphasise that there is a high potential for blockchain enabled digital twins to automate payment processes as well as trading of tokenised data sets on decentralised marketplaces. Their paper only mentions that there is such promising possibility, but the authors do not explain how this potential could be leveraged in more detail nor do they analyse a problem that would be solved.

Zareiyan and Korjani (2018) suggest using blockchain for a 3D printing value chain. The paper does conceptualise remuneration of designers for selling their designs to manufacturers (see figure 4). However key aspects of a system such as FCOS are missing. For example,, how source-available or free and open designs would contribute to such a system is not assessed. Besides, there is no analytical comparison to collaborative development of designs of intangible goods. Further, Zareiyan and Korjani (2018) do not draw insights from peer production. Their paper depicts copyright for protecting economic interests of designers, which is a mistake because copyright does not protect from economic exploitation of physical derivatives of designs, only patents do. In sum, the concept of the paper has some similarities to a system such as the FCOS but does not reach the economic viability, technical level of detail and overall conceptual sophistication.

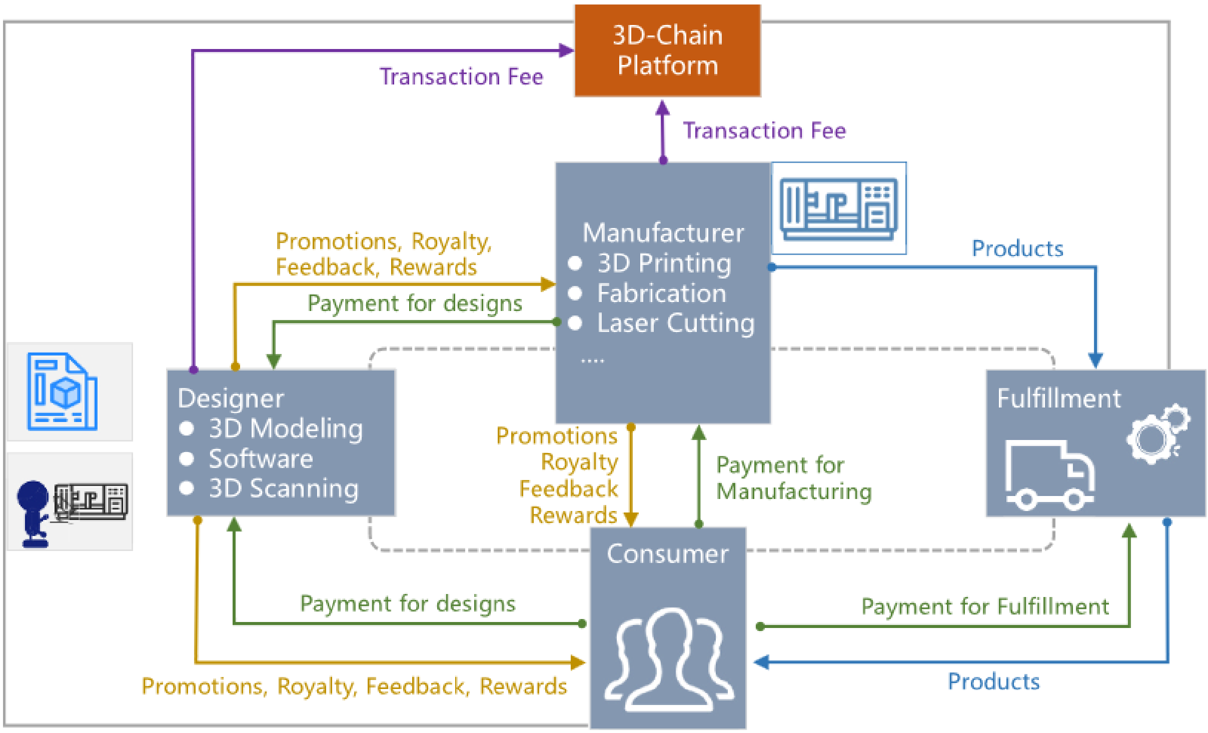

Figure 4: Illustration of 3D Chain Platform Concept

Source: Zareiyan and Korjani (2018)

Narayan and Tidström (2020) explore how perceiving products not as single entities but as social networks enables the conceptualisation of a transition towards circular value chains by employing tokenisation. It does not conduct an economic analysis of developing physical products or their documentation in networks. The paper remains at a high level of abstraction. One could subsume parts of this study under Narayan and Tidström (2020) but that would be a far-fetched undertaking, because the authors are, as said, relatively unspecific.

Manski & Bauwens (2020) come relatively close to a key analytical insight developed in this study. They propagate global design and local manufacturing, but they do not address the issue that hardware design is generally more costly for the average contributor compared to software or text design. Although, the IP and knowledge sharing regime they advocate for are so-called peer production licenses, which emphasise strong reciprocity and acknowledge a potential for restricted sharing. Their intention here is to prevent the designs from being created by “volunteers” and then exploited by capital-oriented companies without remunerating the “volunteers”. So, peer production licenses in theory do allow for the restriction of the economic exploitation of designs. Peer production licenses are not sufficient for protecting hardware, rather for cultural goods such as music and literature. So, the peer production license could be used for the build manual or the whole documentation of a hardware artefact. But if a for-profit company produces and sells the hardware product in masses, the peer production license would not restrict them. In this case, the company would not be allowed to sell the build manual and documentation. Patents are far better suited, but these are argued against strongly by Bauwens and other prominent P2P advocates.

To sum up, only Ayran et al. (2021) bring up the aspect of financial reward mechanisms for enhancing the diffusion of collaborative product development, but they restrict their concept to collaboration on one local site for each product and miss the potential network effects of digital platforms or federated ecosystems. Except for them, Zareiyan and Korjani (2018) and Manski and Bauwens (2020) to some degree, no paper mentions the essential suggestion to let original contributors participate in the economic exploitation of their contribution or its derivatives. Therefore, the concept developed in this study can be considered as an original contribution.

8.7 Synthesising with Perezian State Action - Smart Policy for Leveraging Peer Production for Green Growth - The Significance of Finance to Invest in Production

The previous chapters laid out foundational insights from which the concept of a digital infrastructure such as the FCOS was derived. The concept delivers a viable possibility for leveraging the forces of peer production for a green growth economy. So far, the concept has only been described as if it were in a fully operational mode. The aim of this chapter is to give an answer to RQ4 by elaborating on how a system like the FCOS could be actually implemented. Therefore, the TEPS framework is utilised. This is synthesised with the EU-level European Green Deal legislation and the lower-level legislation of German federal states.

To begin with, key insights are brought to the forefront. The first is that an economy that unfolds on top of an infrastructure such as the FCOS would be subject to network effects, as described in chapter 6.3.3. This leads to a developmental dynamic where there would be a point of self-enforcement, upon which no further external subsidisation, infant industry protection or other similar measures would be required for the system to sustain itself. However, before the development has reached the point of self-enforcement, a systematic policy agenda of supporting such development would increase the chances of success substantially. The policy agenda up until the point of self-enforcement is reached is not necessarily of financial subsidiary nature. As will be laid out below, especially in school education and vocational education curricula, a high potential for steering existing forces into a coherent direction exists.

It is a decisive aspect to presume the organisational and institutional underpinning of a system such as the FCOS, which can be thought of in many different ways. However, the insights from this study only allow for arguing for or against some options, while in other aspects, which type of institutions and organisations to choose is optional. A type of organisational arrangement to argue against is a platform hosted by a single company or a small group of companies, which one could call the conventional startup way. One reason for this is that a federated system with a multitude of different types of institutions all contributing to hosting nodes of the system is more reliable and trustworthy, because there is no single point of failure. Another reason is that an economy unfolding itself upon the FCOS has a high marginal cost at the local and physical level, whereas these costs are low at the global and digital level. As laid out in chapter 6.3.2, profits are therefore gained at the local level and not at the global level. Specifically, whenever the source available hardware documentation is transferred into physical objects, i.e. manufacturing takes place, from a microeconomic welfare perspective it is appropriate to demand a pay. Compared to the linear economy of today, this would bring about a much more equal distribution of wealth generation among the actors involved in the supply chain. It also means that many more local actors with more economic power are involved, as argued in Seidel & Roio (2021). These economic actors would demand agency over the governance of the digital infrastructure upon which their economic operation relies. This should be reflected in a decentralised governance structure of the system.

The following section explores what the TEPS framework suggests to influence the trajectory of a TEP towards a golden age. According to Perez (2010), as mentioned in chapter 3.1, there are three areas of practice and perception within which TEPs manifest, which are applied to the context of this chapter below:

1) In the dynamics of the relative cost structure

2) In the perceived spaces for innovation

3) In the organisational criteria and principles

As mentioned in chapter 3.1, a TEP manifests itself in shaping the dynamics of the relative cost structure. Hereby, a cheap input resource which makes the new way of production more lucrative compared to the old one is key. The input resource for the ICT paradigm to go into the direction of green growth is the information about the product, i.e. the hardware documentation. If this is publicly available, it becomes more economically viable to remanufacture the product locally. The same is true downstream the value chain. It is more likely that a product is repaired, updated or its parts recycled when information about how it has been produced, how it can be disassembled, which updates are available and which materials have been used is openly accessible. With software such as the FCOS, this information becomes openly available. So, it is such software (the digital infrastructure) that steers the ICT paradigm towards becoming more circular, i.e. green. In addition to the source-available information as the main input factor in an increasing amount of products, the accessibility of physical infrastructure is a key facet in the dynamics of the relative cost structure, as described by Spaeth and Hausberg (2016). This accessibility decreases the cost of manufacturing prototypes significantly. Anyone with an idea can go to a local microfactory or Fab Lab and use the machinery to implement the idea. Low threshold access to tools for digital fabrication for individuals and companies is core to the idea of Fab Labs (Fab Foundation, 2024).

The perceived spaces for innovation change with FCOS[22]. The threshold for consumers to engage in the design process decreases significantly. Scanning a product's unique identifier leads one straight to a global community which develops and produces the respective product as well as to the source files of the hardware documentation. For example, when a customer has an idea for how to enhance the quality of a product, because it breaks at a certain point, this customer can simply open a ticket in the repository and start collaborating with the community on this idea. In total, this leads to a massive unleashing of the intellectual and innovative power of the masses. The more a peer production-fuelled green growth economy diffuses, the more it shapes the economic imaginary. This could manifest in talented engineers offering their skillsets to networks of hardware documentation development, just as it is today with software developers who often can work from anywhere anytime. These developers thereby become so independent that they can switch the product they work on frequently. The more a decentral

[22] 'FCOS' stands for all types of this digital infrastructure.

physical infrastructure is in place, a similar trajectory for engineers or even not formally trained designers who have proven their skills in public repos could occur. Such a scenario can lead to less redundancy in the employment force of companies, because they can flexibly hire hardware developers around the world. In total, this would lead to an overall welfare gain.

For applying the third area of practice and perception, the organisational criteria and principles, to a system such as FCOS, one may first recall that chapter 3.1 stated that the ICT paradigm's new 'common sense' are economies of scope. At the local level, the transition towards green growth is also enhanced with the deployment of physical infrastructure across all neighbourhoods. Microfactories (or Fab Labs, open workshops, etc.) indicate spaces where such physical infrastructure is concentrated. Each mircofactory can manufacture a very large range of different hardware. This is because in the source available and OSH space, the manufacturing machines tend to be standardised and interoperable as in the concept of the Open Lab Starter Kit (Omer et al., 2024). Hence, microfactories can spread the cost of operating the manufacturing space across this wide range of different products, which makes it subject to economies of scope. With an increasing amount of hardware documentation accessible through the FCOS federated network, the economies of scope increase.

Another aspect of the organisational principles is that in an economy that is based on an FCOS infrastructure, the economic actors that are engaged in the development process are much more globally dispersed then they are in the linear economy. This is a logical result of the low threshold for engaging in the development. As discussed in chapter 5, there are still higher marginal and transaction costs compared to mere digital information, but nevertheless these costs are substantially lower compared to today. Collaborating with global partners, whether individual peers or firms, would become much more the norm. Consequently, as learned in chapter 3.1, a new TEP changes the 'common sense', which in the ICT paradigm largely means decentralisation.

With the argument of economies of scope in mind, it is important to elaborate on the potential of policies at the local level. It is one of the spaces where forces of the masses can be effectively accumulated to engage in the emerging new economy. A very significant part of this potential of local policies in the German federal system are the educational policies within the jurisdiction of federal states. The principles of action of such policies are to make students familiar with engaging in the FCOS and understanding how it leads to a green growth economy. This increases the chances of the students contributing to the new economy as consumers or producers. Similar support of OS software through such software being part of the curricula in federal states is taking place in the federal state of Lower Saxony, for example.

At the EU level, the European Green Deal and the ESPR legislation create a more favourable setting for the FCOS and its economy to unfold. It is very significant that, due to the ESPR, nearly all physical products on the EU market are going to have a DPP. Once a company knows that it has to overcome the hurdle of implementing a DPP up its value chain, the consideration of an alternative like a FCOS is attractive, because within the FCOS there are at least new business opportunities in terms of diversifying operations and income channels. Gathering upchain data is a significant effort. Since companies have to overcome this hurdle anyway, engaging in a FCOS means far less additional effort. As it can be assumed that the EU will successively increase the ecodesign requirements after DPPs are implemented, it is the more economic choice for producers to change the business model in a way that ecodesign becomes a positive revenue factor. In so doing, the designer increases turnover when the product adheres to ecodesign. As chapter 7 laid out, the FCOS provides this opportunity. One way the FCOS does this is by remunerating the initial designer when the physical derivative of the design gets updated, upgraded, repaired or its materials get recycled. The ecodesign performance can be assessed, and products which adhere more highly to ecodesign can be remunerated more.

The diffusion of a TEPS unfolds in self-enforcing feedback loops between products and infrastructure. In this case, the FCOS is the infrastructure and products are the hardware documentation and its physical derivatives spread on it. For example, a consumer receives a hardware product from the FCOS as a gift. The consumer has not heard of the FCOS. Now, when this consumer wants to upgrade the firmware of the gift, the digital identifier is scanned which establishes a gateway to the FCOS. The consumer then may recognise the benefits of the FCOS and its products and considers purchasing there directly in the future.

Another key element in the transition towards a golden age of a TEP is steering finance. Perez is explicit about the significance of finance for diffusing the new mode of production by establishing institutions and conditions that make finance go into financing production in the new form of production. With tokenisation of repositories, these can become financial investment opportunities for investors. A designer could request funding to mature a design, giving an investor shares to the repository in return. Hereby, the investor acquires claims for future economic exploitation of the design or its physical derivatives. It would be an appropriate policy to reduce regulation and bureaucratic hurdles for this and give tax cuts to sales and profit from the income of such sources. In that case, finance would directly invest in physical production in a way that leverages forces of peer production for green growth.

9. Limitations and Outlook

An argument against the QCA findings could be that peer production of intangible goods already started earlier and therefore has higher numbers of contributors, whereas digital collaboration of tangible goods' documentation is still relatively new and therefore needs some more years in order to display projects with similar PPCs. For such a comparison, one has to define a starting date or at least decade for each branch. Without that, one could compare the growth rates of both branches, but quantifying the total amounts is also quite sophisticated. Nevertheless, the theoretical and empirical arguments of this study stand.

The PPC presumes that all 'commits' are of the same value, but they are not. It is assumed that the variance of value is subject to patterns which result in the PPC staying valid. Future research could take a deeper look into this to find out whether the assumption is valid.

As for another outlook on future related research, the major question is whether the infrastructure as developed in this study will be installed. If forces of peer production are not leveraged for green growth, then the main claim of this study would be falsified. If such infrastructure is not installed, or similar infrastructure that lacks critical elements is installed, then it would depend on the specific context as to whether claims of this study could be falsified. In any case, the major European Green Deal legislation and its outcome will be a relevant field of study for the subject of this study. It is possible that the mass introduction of DPPs will lead to such stark delve in transaction costs of engaging in the development of hardware that peer production becomes a relevant economic governance regime in the development of hardware, even without an infrastructure like the FCOS.

The research at hand follows a realistic epistemology in the sense that in some aspects the author believes that things are to be viewed from a positivist perspective but in some cases an interpretivist perspective is more suitable. The researcher's partly inside position regarding the object of study could be a threat to the overall objectivity. Therefore, this is made transparent and the reader can decide whether the reasoning is objective.

One more aspect future research could address is scraping together larger data sets of Git repositories. Such large data sets would enable testing some of the hypotheses of this study in a way this study did not. Through this, this study's QCA could be supplemented with linear regression to find out whether there is a correlation between hardware, success and financial compensation. It would in fact serve the research to compare average PPCs of all software and hardware projects in each class. The educated guess, informed by the results of this study, is that software would have higher PPCs, i.e. be more equally distributed. Although the author of this study is convinced that the results of analysis of such larger data sets would not challenge this study's outcomes, it would in any case either strengthen or falsify this study's claims. Were this study's claims additionally backed by analysis of larger data sets, the policy implications derived from it would potentially have more force to be implemented at last, which would at least make such larger data set analysis a worthwhile undertaking. On the other hand, if this study's basic claims were falsified by larger data sets analysis, then that would be, for the sake of science, also good discovery. In addition, future research could pick up on Hausberg and Spaeth's (2020) insights on the motivation of contributors to OSH. It cannot be ruled out at this point that the remuneration of some contributors could lead to a crowding out effect of rather intrinsically motivated contributors.

For the economic governance hypothesis along the value chain however, only actual tests of the software can reveal whether the hypothesis made in this study is valid. So, it remains a task for future research to study the effects of adoption of software such as the FCOS on economic governance structures. In addition, one may argue that the economic governance prediction is pre-empted by the description and analysis of each phase of the value chain, because the description already implicates the governance regime. However, the positioning of the prediction chapter after the one describing and analysing, is justified because the reader needs to know where the classification of whether phases are subject to marginal and transaction cost comes from. Otherwise, the reader would need to skip back and forth in the text to comprehend the conclusions. That being said, the structure of this study and its chapter positions do not change the economic reality.

A limiting aspect to mention is this study's focus on the development and invention phase of the value chain, which has its roots in the author's field of expertise, the data accessibility and the economic characteristics of the phases. This study's author worked in the field of OSH and software development and invention for several years and the latter phases were a marginal aspect of this work. Second, the data sourced from Git projects does not exist or is not accessible in other phases of the value chain, which impeded empirical studies there. Lastly, the value creation in the development and invention phase is already more digital today compared to manufacturing onwards, which makes it more prone to an analysis of its potential for peer production.

This study focuses on digital infrastructure and not on physical infrastructure. Nevertheless, for a GGEPP to unfold, a certain physical infrastructure, meaning local manufacturing capacity, is necessary to reach a desirable degree of sustainability. A system such as the FCOS could also facilitate products that are mass produced and shipped across the globe. In a realistic scenario this would still be the case, but it would fade out after time, because the incentive structure promotes local after-manufacturing of products that last much longer. This reduces the number of new products sold. Therefore, local manufacturing would flourish successively.

10. Conclusion

To summarise, this research shows that forces of peer production can be leveraged for green growth. The research specifically explores how this could be achieved, and the four research questions were answered.

At the outset, this dissertation justified its research. The justification was based on three levels. The first one is that the European Green Deal legislation enforces increasing degrees of openness of physical products' hardware documentation, which partly manifests in the mandatory implementation of DPPs. Following Coase (1937), a cut in transaction cost can lead to a change in economic governance regime, specifically peer production in the realm of information production (see Benkler, 2002). Hence, it is important to understand the dynamics of the massive opening of production data and thereby reduction of transaction costs that the EU economy is set to undergo in terms of changing the overall economic governance regime. The second level this dissertation substantiates its justification on is an analytical gap regarding a specific research and activist stream around OSH Movements, the Fab City Foundation, the Fab City Hamburg Association, the P2P Lab and the P2P Foundation. This stream does not sufficiently differentiate between the economic characteristics of tangible and intangible goods and therefore insinuates peer production of hardware. The third level of justification for this research is the author's personal insights from practice in both OSH and software development for several years in a diverse set of projects and organisations. This experience showed how peer to peer ideology, which originated from peer production of intangible goods, encounte rs significant challenges in the physical realm. Together, these three levels of justification form a solid base for the four research questions of this study.

RQ1: To what extent does peer production of hardware occur compared to inherently digital goods such as software?

RQ2: What is a suitable economic governance in phases along a product's value chain where the forces of peer production are leveraged for a green growth economy?

RQ3: To the extent that peer production of hardware can exist, what would an economy look like that leverages this potential?

RQ4: Adopting the TEPS framework, what are effective approaches for a transformational path to leverage the forces of peer production for a green growth economy in the ICT paradigm in the context of the European Green Deal?

Before answering the research questions, this research was positioned in line with, or alongside, different existing research streams. Subsequently, the methodology explored both theoretical and empirical elements. Theoretically, the research was given a framework by Carlota Perez's (1985, 2002 & 2010) TEPS theory. This theory is well-suited to this research, because it explains the dynamics of a change in the mode of production and provides an understanding of the interrelatedness of technological and economic development. For examining the diffusion of peer production into new realms, the object of this study, understanding the interrelated dynamics of technological and economic developments are crucial. Regarding RQ4, the TEPS framework does provide answers for how such change can be governed at all as well as how this can be conducted in a way that the forces at play are harmonised to reduce frictions such as high rates of unemployment.

Having given reason for choosing the TEPS as a theoretical framework, the methodology section continued with arguing for the relevance of a clear definition of peer production. The main reasons for focusing on the definition of peer production are that 1) in literature and practice the definition varies substantially and 2) with a clear definition, more replicable and precise answers to the study's RQs become possible, especially with regards to the empirical aspects. This stated, chapter 6 conducted an investigation into the dynamics of the occurrence of peer production in digital collaboration in the development of hardware. The basis for this was a fsQCA of cases of digital collaboration in the development of hardware and software. The outcome was then tested with a literature review and analysed with three different microeconomic methods. Together, this method promised to give a solid understanding of the dynamics of the occurrence of peer produced hardware documentation. Led by that acquired knowledge, chapter 7 introduced tokenisation as an element which is suitable to leverage forces of peer production for the development of hardware. Finally, chapter 8 synthesised the previous findings with the European Green Deal legislation and the TEPS framework. As part of that, a generic understanding of a GGEPP was derived from the previous findings. With this basis, an extending adaptation of transaction cost economics as applied in Benkler (2002), was used to develop a suitable economic governance arrangement for a GGEPP. Following up, the previously introduced analysis of Kostakis & Bauwens (2014) to distinguish capital and commons on one axis and central and decentral on another axis, was applied to identify the essential factors for enabling a more commons-oriented approach. With the previous insights as a foundation, a sound digital infrastructure was developed upon which a GGEPP could unfold.

Following the methodology section, the TEPS theory was introduced as the theoretic framework of this study. Essential aspects of the TEPS theory for the research topic were depicted. Besides being well suited to explaining the dynamics of a change in the mode of production and providing an approach to govern such change (RQ4), there are some aspects to be recaptured here. First, TEPs are initiated by important technological breakthroughs, for example, Intel's microprocessor was what started the current ICT paradigm. As such paradigms evolve, they change not only what an economy produces but also how it operates, i.e. the mode of production. After some time of frenzied growth, paradigms reach a turning point, which is usually where an economic crisis occurs. In the case of the ICT paradigm, the dot.com bubble burst at the turn of the millennium and only a few years later the crises launched by the bankruptcy of the Lehman Brothers bank marked a double-crises. It was then shown how policies lead to a mature phase of the paradigm where the forces at play are harmonised. The foremost important aspect here is that finance was directed to invest into production capital. Regarding the current paradigm, how a synergistic policy agenda would have green growth as its goal was elaborated on. Finally, this was again synthesised by making use of the TEPS framework. Hereby, an outline of a technology governance approach was developed.

Chapter 4 set out to describe selected aspects in the context of the European Green Deal legislation. It started out by giving a short introduction into green growth or the circular economy. Afterwards, the chapter described aspects of the legislation that are highly relevant to the research topic. This was begun by explaining the rationale behind the legislation which centres around the concept of ecodesign where products are designed in a way that they are durable, repairable, upgradeable, modular, etc. Hereinafter, chapter 4 described and analysed the working mechanism of how the ESPR is to achieve ecodesign implementation. It was pointed out that a green transition that is enforced by raising standards causes potentially more friction compared to a working mechanism where businesses are made to go green due to economic incentive structures. Finally, chapter 4 concluded by depicting DPPs in general and how they are implemented by the ESPR.

Subsequently, RQ1 is answered by first giving an introduction to and defining peer production. To that end, chapter 5 continues by presenting Benkler's (2002) approach of explaining the emergence of peer production with transaction cost analysis. Following, chapter 5 concludes by elaborating on specificities of peer produced hardware and its documentation in more depth. The analytical differentiation between hardware and its documentation is substantial for approaching an answer to RQ1, because what could realistically be peer produced are only digital aspects of hardware, for example its documentation or firmware. In addition, its documentation is always just an imperfect abstraction of the actual physical artefact, which sets it apart from inherently digital goods such as software or text. Having established that foundation, chapter 6 continued by aiming for an understanding of the dynamics of the occurrence of peer production in digital collaboration in the development of hardware. Therefore, chapter 5 conducted two analyses (fsQCA1 and fsQCA2) of cases of digital collaboration in the development of hardware and software. As part of the development of the fsQCA, the chapter worked up a

PPC that enables cases to be ranked along their degree of adherence to peer production according to its definition derived from transaction cost economics. Essentially, the outcome of fsQCA1 was that the presence of hardware predicts the absence of high values on the PPC. The validity of the results was tested and approved by a robustness test and a sensitivity analysis. To add to the findings, a literature review was conducted which found no studies that could either empirically prove hardware's inferiority in terms of being able to be peer produced compared to inherently digital goods, nor was there a comprehensive and elaborate analysis of why that is the case. So, with fsQCA1, it is empirically proven that hardware hinders the occurrence of high levels of peer production. RQ1 can hence be answered. Compared to inherently digital goods, peer production of hardware occurs less. It was further laid out that peer production of hardware is generally rare and will probably stay rare due to its inherent comparatively higher transaction and marginal costs. Peer production is conducted more so in the production of the digitalised information necessary for hardware to be manufactured, i.e. hardware documentation.

RQ2 asked for a suitable economic governance in phases along a product's value chain where the forces of peer production are leveraged for a green growth economy. To approach an answer, key findings were consolidated. It was established that in the ICT paradigm, peer production has the potential to generate significant economic force and that a golden age of the ICT paradigm is to materialise in a green growth economy. Hence, leveraging forces of peer production for a green growth economy was given reason for. The preconditions for mass contributions to the development, manufacturing and processes of after-manufacturing were identified. Chapter 6's fsQCA1 and fsQCA2 established that online collaboration in the development of hardware documentation has more chance of success if there is an option of financial exploitation of one's contributions or its physical derivatives. This was explained by an analysis of the transaction and marginal costs of the development of hardware documentation. So, a pure form of peer produced hardware is unrealistic, but rather a hybrid form of different economic governance regimes would suit the economic characteristics of hardware.

Based on these insights, a generic understanding of a GGEPP was derived. The value chain was differentiated into phases: 1. Invention and Development, 2. Multiplication of Hardware Documentation through a Federated Network, 3a. Regional E-Commerce: Marketing and Sales, and 3b. Replication of Physical Object (Manufacturing), After-Manufacturing (Use, Update, Upgrade, Repair, Adaption) and Materials Acquisition. The differentiation was based on significant changes in the microeconomic characteristics that occurred at the beginning of each phase, which would result in a change of the suitable economic governance regime at the respective phase of the value chain. For example, when hardware documentation is transferred to a manufacturing site, this is a largely digital process. The digital information gets transferred from one server to another in a split second. The cost of this type of transaction as well as the marginal cost are both significantly lower than they are in the phase of development and invention, because the latter phase comprises more physical processes, as chapter 5.3 showed. With that foundation, the extending adaptation of Benkler (2002) was applied to identify a suitable economic governance regime along the value chain of a GGEPP. Answering RQ2, resulted in the following predictions:

Phase 1. Invention and Development - Firms/Organisations, Markets, peer production

Phase 2. Multiplication of Hardware Documentation - Firms/Organisations, peer production

Phase 3a. Regional E-Commerce: Marketing and Sales - Firms, Markets

Phase 3b. Manufacturing, After-Manufacturing and Material Recovery - Firms, Markets

RQ3 set out the task to state what an economy would look like that leverages the potential of peer production for green growth. This was answered on the basis of the previous findings. Here, the key insight was that forces of peer production can be leveraged for a green growth economy by a hybrid form of economic governance regimes through tokenisation. In combination with the other insights, a value chain was defined, which showed how such an economy would look.

Starting with development and invention, the economy was described by examples of different showcases for each phase. Typically, there would be a distributed design process of geographically dislocated economic actors who coordinate through a software with version control. As one example of such software, the FCOS was described. Each contribution would be referenced on a blockchain. Merge requests would entail value claims, which would grant the one requesting the merge a part of the governance and ownership of the repository. For example, if individual X requested to merge an improved version of a repository, X would request 10% ownership of that project. The current project owners can then evaluate the request and either accept it or negotiate a lower percentage. When the merge is conducted, X gets the ownership and governance that was agreed upon. This grants X the right to vote in future decisions with a respective vote and participate in the financial exploitation of the repository, which is hardware documentation, or its physical derivative in later phases of the value chain. The repository is open for everyone to see, but not free for economic exploitation, which is considered source available.

When the hardware documentation has reached a mature level to be commercialised, it is multiplied through a federated network. Although it may seem trivial to some, it is an economically significant step. The marginal and transaction costs are much smaller compared with the currently prevailing linear economy where goods often need to be shipped across the globe. Just as FOSS on GitHub is accessible around the globe, in an economy developed here, hardware documentation would be. This hardware documentation contains all information necessary to re-manucture the hardware. The repository owners can also choose more open licensing. This shared resource of hardware documentation forms a global digital commons.

In the following phase of the value chain, regional e-commerce takes place. This means that the designs from the federated network are fetched to regional e-commerce webpages. These local stores organise that the hardware documentation becomes a product on a local market.

The e-commerce provider therefore needs to find local manufacturers who are willing to manufacture certain hardware documentation according to the terms of it. For example, repository owners may demand 15% of the price. When the local e-commerce provider has an agreement with a local manufacturer, the product can be offered on the shop webpage. The liability lies within the local realm. Depending on the context, either the manufacturer or the shop owner could be liable for product safety and compliance with local jurisdiction. The shops could theoretically also be Otto.de or Amazon.com, but since it would mean a major change in their business model to being very present and connected at the local level, there is a chance that smaller local e-commerce shops prevail. When products are purchased, the owners of the repository get a cut from the price.

The last phase of the value chain consists of replication of the physical object (manufacturing), after-manufacturing (use, update, upgrade, repair, adaption) and materials recovery. Here, products get manufactured and distributed to the customer. The customer can access the DPP and the repository of the product by scanning a unique identifier on the product. If the customer has an idea for an improvement or requests one, it is very easy to suggest this in the repository directly. Via the DPP, the customer can also see possible updates and upgrades for the product. When such upgrades or repairs are conducted and the customer pays for it, the repository owners also receive a cut from the payment. The initial designers of the products therefore have a financial incentive to design products that comply with ecodesign principles. When modules of the product have finally reached their end of life, the module can easily be disassembled and the materials recovered. Here, the initial designers can also be rewarded financially when their product performs better than other comparable products in an ecodesign sense.

Altogether, an economy where forces of peer production are leveraged for green growth is possible, and how such an economy would manifest was shown. The ecodesign for sustainable production regulation, the directive on repair of goods and the directive to empower customers in the green goods all lay out, at least partly, the setting for a source-available economy to thrive. In this economy, at least HD is peer produced to a significant extent. As this study showed, now and into the foreseeable future, this process itself is quite physical and therefore different to the digital realm in which peer production has so far flourished or become dominant. In the scientific elaboration of CBPP in the context of the TEPS, it is an essential aspect that is worth being emphasised more and understood better. This aspect is what this study seeks to emphasise on. Concretely, this study makes an attempt to empirically prove the significance of the effect of how physical a production process is for the diffusion of peer production. In addition, this study aims at understanding the cases where aspects of peer production are successfully adopted in the production of hardware. Furthermore, this study makes an attempt to suggest how forces of peer production can be leveraged for green growth. Since the marginal costs in the outlined new economy are rather high at the local physical and low at the global digital level, profits will more so be gained at the local level.

With regards to governance, Kostakis & Bauwens' (2014) insight states that forces of peer production can be leveraged in different ways, which can be analysed in terms of being capital- or commons-oriented on one axis and centralised or decentralised on the other axis. Social media is dominated by systems which have a decentralised frontend but a centralised backend which is typically owned by capital-oriented economic actors.

To approach answering RQ4, which pointed towards adopting the TEPS framework to develop effective approaches for a transformational path to leverage the forces of peer production for a green growth economy in the ICT paradigm in the context of the European Green Deal, chapter 8.7 consulted the TEPS framework again. The framework emphasises the role of the state and prescribes general policies to achieve a golden age of the respective TEP. It proves to be particularly useful and relevant that digital economies are subject to network effects. Therefore, in the case of promoting a green growth economy it was explained that a potential state subsidy could be ceased when the new economy reaches a point of self-enforcement. It was then laid out that subsidy policy is not the only option, but that the new economic policy could also be extended to other realms, especially in school and vocational education, because there is a high potential to steer existing forces in a coherent direction, enabling them to complement each other. Furthermore, it was argued that the institutional underpinning of the software should be federated. This would entail a multitude of organisations all contributing to hosting nodes of the system in a very reliable and trustworthy way, which would minimise any single points of failure.

To continue answering RQ4, three areas of practice and perception that every TEP manifests in were explored and applied to the lessons learned so far. These three areas are: 1) the dynamics of the relative cost structure, 2) the perceived spaces for innovation and, 3) the organisational criteria and principles. With regards to 1), the key input resource was identified as information. With a system such as the FCOS in place, information for contributing to the value chain of a green growth economy would be very accessible, or in other words, cheap. This is essential for the economic power of a system such as the FCOS. In addition, low threshold access to manufacturing infrastructure was identified as being important for the manifestation of a golden age of the ICT paradigm. As a result, the relative costs of manufacturing a prototype decrease. An exemplary policy is to have an open workshop (e.g. a Fab Lab or an Open Lab) or microfactory in every neighbourhood of a city. As of 2), the ESPR's implementation of DPPs lowers the threshold for customer engagement with the products repository, because customers can suggest improvements in terms of longevity, for example. For 3), it was recalled that a new 'common sense' of the ICT paradigm is economies of scope, which applies to the economy developed in this study in terms of the vast range of different artefacts that can be manufactured with fewer manufacturing machines, compared to the linear economy. This is one aspect of how decentralisation as a form of the overarching principle of organisation of the ICT paradigm manifests in the derived green growth economy. It was then expounded that the theoretical and practical understanding of how a green growth economy works could be taught in schools. In Germany, because education is in the jurisdiction of federal states, local level policy agendas that leverage the potential of systems such as FCOS can be very effective.

To conclude answering RQ4, chapter 8.7 addressed the significance of finance. According to the TEPS theory, finance plays a major role in the diffusion of a new TEP. How tokenisation of repositories could create investment opportunities for large and small investors was also explained. Investments in these repositories would enable inventors to mature designs and prototypes. Investors would get shares of the repositories in return and participate in the financial exploitation of the hardware documentation or its derivatives. Hence, all four research questions were answered in a scientifically valid way.

This study provides several original contributions that are worth being emphasised. The PPC enables peer production to be quantified. Quantifying peer production for the first time makes it possible to compare projects in terms of how much they are subject to peer production or their degree of peer production. Furthermore, fsQCA1 and fsQCA2 offer new scientifically valid insights into when peer production occurs. The microeconomic analysis of the results of fsQCA1 and fsQCA2 contributes to the understanding of why peer production occurs more so in the development of intangible goods. The derivation of an economy that leverages the potential of peer production for a green growth economy as well as the required digital infrastructure therefore is also original.

It is the intention of this research that OSH enthusiasts and communities such as the Fab Lab and Fab City communities recognise the findings of this research. Especially significant are the different economic characteristics of tangible and intangible goods in terms of marginal and transaction costs. These result in different economic governance regimes, which require different levels of openness. Making free and OS a dogma in the realm of hardware, hinders the potential economic and transformational force.

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Appendices

Kurzzusammenfassung

Die vorliegende englischsprachige Dissertationsschrift dokumentiert eine Untersuchung der Produktionsmethode p*eer production*, also dezentraler Produktion mit hoher Granularität und Selbstzuweisung der Arbeit, im Kontext der Durchsetzung der Wirtschaftsform *green growth* in Anlehnung an Carlota Perez' Theorie der Techno-Ökonomischen Paradigmenwechsel. Hauptsächliches Wesensmerkmal von green growth ist eine Entkopplung des Wachstums (BIP) vom Wachstum des Ressourcenverbrauchs.

Ein Anlass der Untersuchung war, dass peer production bei der Entwicklung von immateriellen Gütern teilweise bereits frühere Formen des Wirtschaftens verdrängt hat, und vor diesem Hintergrund in Teilen von Wissenschaft und Praxis angenommen wird, dass peer production von physischen Gütern ebenfalls möglich ist. Diese Annahme ist eher implizit als explizit formuliert und deswegen umso wichtiger in Frage zu stellen, weil sie gegebenenfalls für ausbleibenden Erfolg der Praxis beziehungsweise falsche Aussagen der Wissenschaft verantwortlich ist, ohne dass dies erkannt würde. Der Verfasser dieser Schrift war selbst aktiv in der Praxis der Umsetzung auf Grundlage der genannten Annahme involviert, was sowohl Software- und Hardware-Entwicklung und -Verbreitung von Infrastrukturen für die Nutzbarmachung von peer production für die Durchsetzung von green growth umfasste, als auch die Entwicklung und Verbreitung der Produkte (genauer als Artefakte zu bezeichnen) mit Infrastruktur dieser Art selbst, umfasste.

Eine weitere Rechtfertigung der Untersuchung ist eine Verschärfung der sogenannten Ökodesignverordnung durch die EU-Kommission, die eine sukzessive aber verpflichtende Einführung digitaler Produktpässe für nahezu alle physischen Güter auf dem EU-Markt vorsieht. Damit wird die Chance der Realisierung des beschriebenen angenommenen Potenzials von peer production für physische Güter erhöht, weil die Güter damit allgemein digitaler werden und sich somit eher dezentral vervielfältigen lassen.

Der Fokus der Untersuchung liegt zunächst auf der frühen Phase der Wertschöpfungskette von Hardware, also physischen Gütern. Konkret ist die erste Forschungsfrage, inwieweit peer production von Hardware, im Vergleich zu inhärent digitalen Gütern, wie etwa Software, vorkommt. Um diese Frage zu beantworten, definiert diese Studie genauer, was für sie peer production ist und greift dabei auf eine etablierte transaktionskostenbasierte Herleitung der Produktionsmethode zurück. Darauf aufbauend stellt sie den *peer production-coefficient* (PPC) auf, mittels dessen messbar wird, inwieweit die Entwicklung eines ökonomischen Gutes dem zuvor definierten Verständnis von peer production entspricht. Der PPC wird anschließend auf verschiedenartige Git-basierte Hardware und inhärent digitale Güter angewandt. Mittels der fuzzy-set Qualitative Comparative Analysis (fsQCA) werden die unterschiedlichen PPC-Ergebnisse verglichen. Das Ergebnis des Vergleichs ist, dass physische Güter mit geringeren PPC-Werten entwickelt werden und die erste Forschungsfrage insofern beantwortet werden kann. Bei den über 60 untersuchten ökonomischen Gütern entspricht die Entwicklung jener eher der peer production, die inhärent digital sind. Es wird zugestanden, dass die Datenbasis zwar nicht unrepräsentativ ist, aber es für die Zukunft Sinn ergibt, für eine größere Aussagekraft, eine umfangreichere und breitere Datenbasis zu verwenden.

Darüber hinaus werden durch die Anwendung verschiedener weiterer qualitativer und quantitativer Methoden, insbesondere fsQCA des erwähnten Datensatzes, Bedingungen identifiziert, unter denen digital und dezentral entwickelte physische Güter, eher erfolgreich seien können. Finanzielle Kompensation der Beitragenden sticht hierbau heraus. Dies ist in Einklang mit der transaktionskostenbasierten Herleitung von peer production, wonach die höheren Transaktionskosten physischer Güter zu einer geringeren Granularität der Zusammensetzung der Beitragenden führt. Für den Erfolg physischer Güter ist es also förderlich, wenn durch finanzielle Kompensation ermöglicht wird, dass die einzelnen Arbeitspakete in der verteilten Entwicklung größer sind. Nimmt sich beispielsweise eine individuelle Entwicklerin mehr Zeit für ihren Beitrag, ist es ihr tendenziell erschwert möglich, dieses in ihrer nicht finanziell vergüteten *Freizeit* zu tun.

Aufbauend auf dieser Erkenntnis wird mit der Beantwortung der zweiten und dritten Forschungsfrage entlang der Wertschöpfungskette physischer Güter, die digital entwickelt werden, bis zur Rezyklierung einzelner Materialien anhand der Transaktionskosten abgeleitet, welche Art der Ökonomie die jeweils durchsetzungskräftigste ist. Nach Yochai Benkler wird hierbei zwischen Markt, Unternehmen und peer production unterschieden. Dafür wird eine digitale Infrastruktur skizziert, auf der sich eine Ökonomie entfalten könnte, die auch mittels peer production green growth erreichen könnte. Schließlich wird für die Beantwortung der vierten Forschungsfrage darauf eingegangen, was, anhand der Theorie der Techno-Ökonomischen Paradigmenwechsel, effektiv Ansätze sind, einen Transformationspfad hin zu green growth zu betreten.

Die Arbeit ist in einer erkenntnistheoretischen Haltung des kritischen Realismus verortet und steht ontologisch auf dem Fundament eines Tanach-basierten Weltbilds, das die Welt als sinnvoll geordnet und den Menschen als verantwortlichen Mitgestalter versteht. Insgesamt leistet die Studie einen originären Beitrag zur Operationalisierung und Bewertung von Peer Production im Kontext nachhaltiger Transformation, entwickelt konzeptionell Infrastrukturen zur Förderung derselben und bietet eine zukunftsgerichtete Perspektive auf deren systemische Verankerung im aktuellen techno-ökonomischen Paradigma.

Executive Summary

The English-language dissertation at hand documents an investigation into the production method *peer production*, which is decentralized production with high granularity and self-assigned tasks, within the context of advancing the economic model of *green growth*, in alignment with Carlota Perez's theory of techno-economic paradigm shifts (TEPS). The defining feature of green growth is the decoupling of economic growth (GDP) from the growth of resource consumption.

One of the motivations behind this research was the observation that peer production has already replaced earlier forms of economic governance regimes in the development of intangible goods. Against this background, it has been implicitly assumed in parts of science and practice that peer production of physical goods is also possible. This assumption, however, is rarely made explicit and therefore needs to be critically examined, as it may contribute to a lack of success in practical implementations or flawed conclusions in scientific discourse, without being recognized as the root cause. The author of this work was personally involved in such practical implementations, both in the development and dissemination of infrastructures intended to enable peer production in support of green growth (including software and hardware), and in the development and diffusion of the resulting products (artefacts) themselves.

Another justification for this research lies in the tightening of the EU's Ecodesign Directive, which foresees the gradual but mandatory introduction of digital product passports for nearly all physical goods on the European market. This shift increases the feasibility of the assumed potential of peer production for physical goods, as it contributes to the digitization of these goods and thus enhances their capacity for decentralized reproduction.

The study primarily focuses on the early phase of the value chain of hardware, i.e. physical goods. The first research question addresses the extent to which peer production of hardware occurs in comparison to inherently digital goods such as software. To answer this question, the study defines more precisely what is meant by *peer production*, drawing on an established transaction-cost-based derivation of the concept. Building on this, the study develops the *Peer Production-Coefficient* (PPC), a metric designed to quantify the extent to which the

development of a particular good aligns with the defined concept of peer production. The PPC is applied to various Git-based hardware projects (resulting in economic goods) as well as inherently digital goods. The results are then compared using fuzzy-set Qualitative Comparative Analysis (fsQCA). The outcome of this comparison reveals that physical goods tend to be developed with lower PPC scores. Insofar, the first research question is answered: among more than 60 analysed economic goods, those that are inherently digital are more closely aligned with the characteristics of peer production. Although the dataset is not unrepresentative, the study acknowledges that future research would benefit from a broader and more comprehensive dataset to enhance generalisability.

Beyond this, the application of various additional qualitative and quantitative methods, especially further fsQCA analyses of the dataset mentioned above, enables the identification of conditions under which digitally and decentrally developed physical goods are more likely to be successful. A key finding here is the importance of financial compensation for contributors. This aligns with the transaction-cost-based derivation of peer production, in which the relatively higher transaction costs associated with physical goods tend to reduce the granularity of contributors' involvement. Therefore, the success of physical goods in peer production environments is more likely if larger work packages can be made viable, something that financial compensation helps facilitate. For example, if an individual developer is to invest more time into her contribution, it becomes more difficult to do so purely in unpaid free time.

Building on this insight, the study addresses the second and third research questions by analysing the value chain of digitally developed physical goods through to the recycling of materials. It derives which type of economic governance, market, firm, or peer production (following Yochai Benkler), is most suitable at each stage, based on transaction cost considerations. A digital infrastructure is outlined upon which an economy could develop that leverages peer production to achieve green growth. Finally, to address the fourth research question, the study draws on the TEPS theory to explore what kinds of policy and systemic approaches might initiate a viable transformation path toward green growth.

This research is rooted in an epistemological stance of critical realism and is ontologically grounded in a Tanakh-based worldview, in which the world is seen as purposefully ordered and humanity as a responsible co-creator within that order. Ultimately, the study contributes an original framework for the operationalisation and evaluation of peer production in the context of sustainable transformation, develops conceptual infrastructures to support it, and offers a forward-looking perspective on how peer production may become systematically embedded within the current techno-economic paradigm.

Erklärung

Hiermit erkläre ich, Benedikt Seidel, dass ich keine kommerzielle Promotionsberatung in Anspruch genommen habe. Die Arbeit wurde nicht schon einmal in einem früheren Promotionsverfahren angenommen oder als ungenügend beurteilt.

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Eidesstattliche Versicherung

Ich, Benedikt Seidel, versichere an Eides statt, dass ich die Dissertation mit dem Titel:

„Leveraging Peer Production for a Green Growth Economy"
selbst, und bei einer Zusammenarbeit mit anderen Wissenschaftlerinnen oder Wissenschaftlern gemäß den beigefügten Darlegungen nach § 6 Abs. 3 der Promotionsordnung der Fakultät für Wirtschafts- und Sozialwissenschaften vom 18. Januar 2017, verfasst habe. Andere als die angegebenen Hilfsmittel habe ich nicht benutzt.

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