Blockchain Systems as Multi-sided Platforms

Juri Mattila

Aalto University | DOCTORAL DISSERTATIONS 122/2021
ETLA Economic Research | Series A, No 51

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A doctoral dissertation completed for the degree of Doctor of Science (Technology) to be defended, with the permission of the Aalto University School of Science, on 29th October 2021 at 16:00.

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Aalto University publication series
DOCTORAL DISSERTATIONS 122/2021

ETLA Economic Research Series A, No 51

ISBN 978-952-64-0503-2 (printed)
ISBN 978-952-64-0504-9 (pdf)
ISSN 1799-4934 (printed)
ISSN 1799-4942 (pdf)
http://urn.fi/URN:ISBN:978-952-64-0504-9

ISBN 978-951-628-711-2 (printed)
ISBN 978-951-628-712-9 (pdf)
ISSN-L 0356-7435
ISSN 0356-7435 (printed)

Next Print Oy
Helsinki 2021

Finland

Aalto University

Aalto University, P.O. Box 11000, FI-00076 Aalto www.aalto.fi

Abstract

Author
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Name of the doctoral dissertation
Blockchain Systems as Multi-sided Platforms

Publisher School of Science

Unit Department of Industrial Engineering and Management

Series Aalto University publication series DOCTORAL DISSERTATIONS 122/2021

Field of research Industrial Engineering and Management

Manuscript submitted 31 May 2021 **Date of the defence** 29 October 2021

Permission for public defence granted (date) 23 August 2021 **Language** English

☐ **Monograph** ☒ **Article dissertation** ☐ **Essay dissertation**

Abstract

Ever since its discovery, blockchain technology has been heralded as a disruptive innovation for the digital economy. Today, more than a decade later, however, the digital society still seems largely untransformed by blockchain. Was the biggest hype phenomenon since the dot com bubble all just smoke and mirrors—or did something happen after all that we simply missed by looking in the wrong direction?

The definition of 'blockchain' is a notoriously elusive one. Without a structured socio-economic delineation, perceiving and understanding the phenomenon's effects on digitalization is difficult. To this end, this dissertation investigates whether permissionless blockchain systems could be delineated in a structured and comprehensive manner as *digital multi-sided platforms*. By applying a critical realist methodological approach, the dissertation explores public permissionless blockchain systems through a multitude of research methodologies, such as case studies and design science, and several focal perspectives, *e.g.* cost, governance and incentivization. Through the frameworks of multi-sided platform theory and transaction cost economics, the dissertation makes an effort to elucidate the platform characteristics and the transformative impact of blockchain systems to the digital platform economy and digitalization in general.

The dissertation finds that permissionless blockchain systems can be coherently described as multi-sided platforms. Differing from conventional multi-sided platforms in multiple ways, blockchain systems provide an alternative method for deploying, growing and sustaining multi-sided platforms as ahierarchical peer-to-peer networks. Their eccentric growth dynamic enables a new kind of '*fire-and-forget*' approach to platform deployment—but with the trade-off of higher operating costs and platform resource scarcity. Thus, blockchain systems should not be misconstrued as substitutes for conventional multi-sided platforms, or improved versions thereof. Instead, they seem to represent a limited example of a transition from the conventional service-structured business logic towards an even more all-encompassing value co-creation and platform co-opetition perspective than what is facilitated by contemporary multi-sided platforms.

Contributing to the discussion on the transformative impact of blockchain systems, this dissertation concludes that a digital transformation has taken place in their wake over the past decade. However, this transformation seems largely misinterpreted due to poor choices of explanatory frameworks and overinflated expectations. Transcending the more popular perspectives rooted in decentralization, trust, and digital currency, this dissertation paints a picture of this transformation through a lens of platform deployment, vertical integration, and horizontal modularity. By systematically linking the blockchain phenomenon to the comprehensive socio-economic framework of digital multi-sided platforms, the dissertation enables better and more comprehensive exploration of this transformation.

Keywords blockchain, multi-sided platform, network effect, co-opetition

ISBN (printed) 978-952-64-0503-2	**ISBN (pdf)** 978-952-64-0504-9
ISSN (printed) 1799-4934	**ISSN (pdf)** 1799-4942
Location of publisher Helsinki	**Location of printing** Helsinki **Year** 2021
Pages 73 + 150	**urn** http://urn.fi/URN:ISBN:978-952-64-0504-9

Aalto-yliopisto

Tiivistelmä

Aalto-yliopisto, PL 11000, 00076 Aalto www.aalto.fi

Tekijä
Juri Mattila

Väitöskirjan nimi
Lohkoketjujärjestelmät monisuuntaisina alustoina

Julkaisija Perustieteiden korkeakoulu

Yksikkö Tuotantotalouden laitos

Sarja Aalto-yliopiston julkaisusarja DOCTORAL DISSERTATIONS 122/2021

Tutkimusala Tuotantotalous

Käsikirjoituksen pvm 31.05.2021 **Väitöspäivä** 29.10.2021

Väittelyluvan myöntämispäivä 23.08.2021 **Kieli** Englanti

☐ **Monografia** ☒ **Artikkeliväitöskirja** ☐ **Esseeväitöskirja**

Tiivistelmä

Lohkoketjuteknologiasta on sen alkuajoista lähtien povattu digitaalisen yhteiskunnan mullistavaa innovaatiota. Vuosikymmenen jälkeen digitaalinen yhteiskunta vaikuttaa kuitenkin olevan entisellään. Oliko kyseessä vain suurin hype-ilmiö sitten dot com -kuplan, vai jäikö jotakin huomaamatta?

Lohkoketjun määritelmä on pahamaineisen häilyvä. Ilman selkeästi jäsenneltyä sosioekonomista luonnehdintaa, ilmiön digitalisaatioon kohdistuvien vaikutusten havaitseminen ja ymmärtäminen on hankalaa. Tämän väitöskirjan pyrkimyksenä on selvittää, voidaanko avoimet lohkoketjujärjestelmät jäsennellysti ja johdonmukaisesti kuvata *monisuuntaisina alustoina*. Soveltamalla kriittisen realismin metodologiaa väitöskirja tarkastelee avoimia lohkoketjujärjestelmiä useiden tutkimusmenetelmien kautta esim. tapaustutkimusta sekä design science -menetelmää hyödyntäen, ja keskittyen useisiin eri näkökulmiin, kuten kustannus-, hallinto- ja kannustinrakenteisiin. Alustatalouden sekä transaktiokustannusten taloustieteen teorioihin nojautuen väitöskirja pyrkii valottamaan lohkoketjualustojen ominaispiirteitä sekä hahmottamaan niiden muutosvaikutuksia niin alustatalouteen kuin myös digitalisaatioon laajemmin.

Väitöskirjan tutkimuslöydöksenä havaitaan, että avoimet lohkoketjujärjestelmät voidaan johdonmukaisesti kuvata monisuuntaisina alustoina. Vaikkakin lohkoketjualustat eroavat monin tavoin tavanomaisista monisuuntaisista alustoista, tarjoavat ne vaihtoehtoisen tavan perustaa, kasvattaa sekä ylläpitää monisuuntaisia alustoja hierarkiattomina vertaisverkkoina. Niiden omintakeinen kasvudynamiikka mahdollistaa uudenlaisen '*ammu-ja-unohda*' -lähestymistavan alustojen perustamiseen – mutta aiempaa korkeammilla käyttökustannuksilla ja niukasti hyödynnettävin alustaresurssein. Lohkoketjualustoja ei näin ollen tulisikaan mieltää tavanomaisten monisuuntaisten alustojen korvaajina tai paranneltuina versioina. Ennemminkin ne heijastelevat tavanomaisia alustoja pidemmälle vietyä siirtymää pois palvelukeskeisyydestä kohti kokonaisvaltaista yhteisarvonluontia ja kilpailevaa yhteistyötä.

Johtopäätöksenään väitöskirja toteaa lohkoketjujärjestelmien aiheuttaneen digitaalista muutoskehitystä, mutta tavalla, joka on jäänyt vähälle huomiolle harhaanjohtavista tulkintakehikoista sekä ylilatautuneista odotuksista johtuen. Ottaen etäisyyttä hajauttamisesta, luottamuksesta ja digitaalisesta valuutasta kumpuaviin tavanomaisempiin tulkintoihin, väitöskirja maalaa kuvan lohkoketjujärjestelmien murroksesta alustojen perustamisen, integraation ja modulaarisuuden näkökulmasta. Sitomalla ilmiön näin digitaalisten monisuuntaisten alustojen kontekstiin, työ mahdollistaa lohkoketjujärjestelmien muutoskehityksen laajemman ja kokonaisvaltaisemman jatkotarkastelun uudesta näkökulmasta käsin.

Avainsanat lohkoketju, monisuuntainen alusta, verkostovaikutus, kilpaileva yhteistyö

ISBN (painettu) 978-952-64-0503-2	**ISBN (pdf)** 978-952-64-0504-9
ISSN (painettu) 1799-4934	**ISSN (pdf)** 1799-4942
Julkaisupaikka Helsinki	**Painopaikka** Helsinki **Vuosi** 2021
Sivumäärä 73 + 150	**urn** http://urn.fi/URN:ISBN:978-952-64-0504-9

Preface

Emerging technology is like a mirror into the soul. It is a portal reflecting one's hopes and dreams about the future—but also one's fears and insecurities. Like an unmarked harbinger approaching in the distance, emerging technological disruption portends the end of times as they are known, heralding an unavoidable leap into a new unknown. In the face of such uncertainty, we humans are drawn to seek refuge in familiarity. Gazing into this dark mirror, it is always easy to see what one wants to see. The images we can make out in its surface are always bound by the shapes and forms which we already understand from our present reality. Much like the Palantíri seeing stones in the Lord of the Rings, the mirror of technology can unveil a glimpse of the future, but at the same time drive us to draw the wrong conclusion from what has been shown. The true difficulty, in other words, is in seeing the mirror itself.

Having spent the last decade staring into the mirror that is the blockchain phenomenon, I've come to understand that as a porthole into the future, it is an especially devious one. As a faceless entity of exponential growth, it feeds into the hopes and fears of people in ways which most technologies do not. Like a steroid for the imagination, the blockchain mirror can take one's dreams and fears about the future, and reflect them back a hundred-fold amplified, so brightly that the image will leave its viewer blind.

Some have tried to escape the intense glow of the mirror by taking the overly reductionist avenue. By sticking to describing the technical functionality of the blockchain system, they believe they can deconstruct the mirror and see what lies behind it. But of course, the technical shards tell us no more about the emergent phenomenon than examining a typewriter would tell us about Mark Twain.

Others have tried readjusting the mirror so that their amplified dreams can live on. By redefining the linguistic concepts and diluting the terms where necessary, an illusion of 'blockchain-in-the-gaps' can be sustained indefinitely, along the lines of "if it didn't deliver us from evil, it wasn't true blockchain". And some, of course, have chosen to cover the mirror entirely, hoping that "if we do not speak its name, perhaps the harbinger will never come". Yet, there it remains, the mirror, unwaiveringly and as prominently as ever present, while still hiding its true form in plain sight. In our desire to surpass its reflection and to see beyond, we have no choice but to look into the void—even if it involves enduring a great deal of pain.

This dissertation represents my honest and best attempt to portray the blockchain mirror in its true form. While I have undoubtedly been prone to its distortions just like anyone else, I have stared into its face for longer and from more angles than most. In doing so, I have come to know its perfidious tricks, the blind spots that it hides in its ripples, and the resonant sound of its siren call. At times, the quest has been quite an ungrateful one, as people have not always taken kindly to having their soul's image called into question, on both sides of the debate.

Nonetheless, I have tried to remain true to myself and to steer clear of the fanaticism and fervour in my exploration of this strange digital alien lifeform. And yet, perhaps the critics are right. Perhaps what I have portrayed is nothing more than merely the mirror image into my own soul. But even so, the journey has not been a pointless endeavour, as I have discovered a great many things about myself and my own inner perception of reality.

Either way, I hope this body of work has been a worthy contribution, or that it at least makes for an interesting read. If nothing else, I can always take pride in the fact that, all else failing, I will still have provided the world with some good kindling—and anyone who has ever tried to light a fire with damp firewood can certainly recognize the value in that.

6th October 2021 in Helsinki

Juri Mattila

Table of contents

Abstract

Ever since its discovery, blockchain technology has been heralded as a disruptive innovation for the digital economy. Today, more than a decade later, however, the digital society still seems largely untransformed by blockchain. Was the biggest hype phenomenon since the dot com bubble all just smoke and mirrors—or did something happen after all that we simply missed by looking in the wrong direction?

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Contributing to the discussion on the transformative impact of blockchain systems, this dissertation concludes that a digital transformation has taken place in their wake over the past decade. However, this transformation seems largely misinterpreted due to poor choices of explanatory frameworks and overinflated expectations. Transcending the more popular perspectives rooted in decentralization, trust, and digital currency, this dissertation paints a picture of this transformation through a lens of platform deployment, vertical integration, and horizontal modularity. By systematically linking the blockchain phenomenon to the comprehensive socio-economic framework of digital multi-sided platforms, the dissertation enables better and more comprehensive exploration of this transformation.

Acknowledgements

First and foremost, I would like to thank my supervisor Timo Seppälä and my professor Risto Rajala for their extensive support and guidance which enabled the drafting of this dissertation in the first place. I also wish to thank the pre-examiners, professor Anssi Öörni and professor Tuure Tuunanen for constructive comments that helped me to finalize the manuscript. Many thanks also to my opponent, professor Aija Leiponen.

Next, I want to thank the co-authors with whom I've had the privilege to collaborate in the included articles: Kary Främling, Tobias Goodden, Esko Hakanen, Jan Holmström, Taneli Hukkinen, Kristian Lauslahti, Kari Smolander, Pellervo Valkama, and Mika Westerlund.

I would also like to extend my gratitude to the Research Institute of the Finnish Economy (ETLA) as well as Aalto University and their Department of Industrial Engineering and Management for facilitating the research process. Especially, I would like to express my appreciation towards my most influential current and former colleagues in regards to this dissertation: Petri Rouvinen, Antti Tahvanainen, Martti Kulvik, Jyrki Ali-Yrkkö, and Annu Kotiranta.

Several companies provided valuable contributions towards this research. In this regard, I wish to thank Fortum for their extensive collaboration during the research process, and especially Heli Antila, Catarina Naucler, Riitta Ståhl, Marianne Tikkanen, and Alexandra Bådenlid who were very helpful in the drafting of conceptual energy industry use cases in the early phases of the research process. I also want to extend my gratitude to Euroclear Finland for their cooperation, especially Anu Saarinen and Heikki Ylipekkala, as well as Pirkka Frosti from Digital Living. Their inputs in the drafting of conceptual use cases for the financial industry were of great value in the beginning of the process. Furthermore, I would also like to thank Krogerus, and especially Mika Puittinen, Kalle Hynönen, Pessi Honkasalo, and Essi Launonen for their extensive co-operation and valuable insights on the legal aspects and implications of blockchain systems and smart contracts.

Many others who had a supporting role in this project should also be acknowledged for their valuable inputs. In this regard, my appreciations go out to Bruce Pon, Jed McCaleb, Stu Feldman, Henry Brade, Kai Jia, Jeremias Kangas, Aleksi Grym, Brian Fabian Crain, Pekka Nikander, and Riikka Koulu.

I would also like to thank all the institutions and projects that provided funding for this research: the University of California at Berkeley, the Berkeley Roundtable on the International Economy, and the BRIE-ETLA research project; Business Finland, the Blockchains Boosting Finnish Industries research project (BOND), and the Integrating Platform Competences Toward Network Effects research project (iPlate); Academy of Finland, and the Direct Operations research project (DO); the Finnish Science Foundation for Technology and Economics (KAUTE); IBM and the International Society of Service Innovation Professionals (ISSIP); and the Savings Banks' Research Foundation.

Lastly, and most importantly, I would like to thank my family for their unwavering support, especially my wife, Lorna, and my parents Riitta and Raimo, without whom this dissertation would not have been possible, as well as my daughter Lillian for providing endless joy in my life. Love you all.

6th October 2021 in Helsinki

Juri Mattila

List of publications

Article 1

Rajala, R., Hakanen, E., Mattila, J., Seppälä, T., & Westerlund, M. (2018). *How Do Intelligent Goods Shape Closed-Loop Systems?* California Management Review, Vol. 60(3), pp 1–25.

Article 2

Mattila, J., Seppälä, T., Valkama, P., Hukkinen, T., Främling, K., & Holmström, J. (2021). *Blockchain-Based Deployment of Product-Centric Information Systems.* Computers in Industry, Vol. 125(2), pp. 1–14.

Article 3

Mattila J., & Seppälä T. (2018). *Distributed Governance in Multi-sided Platforms: A Conceptual Framework from Case: Bitcoin.* In: Smedlund A., Lindblom A., Mitronen L. (eds) Collaborative Value Co-creation in the Platform Economy. Translational Systems Sciences, Vol 11. Springer, Singapore.

Article 4

Lauslahti K., Mattila J., Hukkinen T., & Seppälä T. (2018). *Expanding the Platform: Smart Contracts as Boundary Resources.* In: Smedlund A., Lindblom A., Mitronen L. (eds) Collaborative Value Co-creation in the Platform Economy. Translational Systems Sciences, Vol 11. Springer, Singapore

Article 5

Hukkinen, T., Mattila, J., Smolander, K., Seppälä, T., & Goodden, T. (2019). *Skimping on Gas: Reducing Ethereum Transaction Costs in a Blockchain Electricity Market Application.* Proceedings of the 52nd Hawaii International Conference on System Sciences.

Author's contributions

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The author of this dissertation participated in the literature review as well as in the conducting of the case analyses for the paper with equal contributions. The writing of the manuscript was a joint effort where the lead author's contribution was the most significant, while the other authors contributed equally in smaller capacity.

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The idea for the paper, the research design, and the theoretical reasoning were joint efforts by the author of this dissertation, the second author, and the last author, with equal contributions. The drafting of the design proposal was a joint effort by the author of this dissertation and the third and the fourth authors. The author of this dissertation conducted and analysed all of the research interviews. The writing of the manuscript was mostly the sole contribution of the first author, with some inputs from the second author, third author, and the last author to the writing process.

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The idea for the paper, the research design, and the literature review on multi-sided platforms were drafted in collaboration by both authors of the paper, with equal contributions. The case analyses, the theoretical reasoning, and the writing of the manuscript, as well as all other inputs were the sole contributions of the author of this dissertation.

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Lauslahti K., Mattila J., Hukkinen T., & Seppälä T. (2018). *Expanding the Platform: Smart Contracts as Boundary Resources.* In: Smedlund A., Lindblom A., Mitronen L. (eds) Collaborative Value Co-creation in the Platform Economy. Translational Systems Sciences, Vol 11. Springer, Singapore.

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1 INTRODUCTION

1.1 Background synopsis

In 2008, a mysterious white paper was posted in a cryptography mailing list in the Internet, outlining a revolutionary concept for a novel peer-to-peer electronic cash system named Bitcoin (Nakamoto, 2008). Published anonymously under a pseudonym, the paper paved the way for the creation of new kinds of decentralized virtual assets, seemingly ushering in a transformational digital disruption of money in the 21st century. What ensued in the following years was the biggest IT hype phenomenon since the dot com bubble.

Now more than a decade later, on the other side of the hype wave in the trough of disillusionment, it seems that the promise of these decentralized virtual assets and their underlying blockchain technology never truly materialized. The disruption by decentralized virtual assets never really took place as anticipated. After more than a decade of mass frenzy, the digital society seems largely untransformed by blockchain—or does it? Did something happen after all that we simply missed by looking in the wrong direction?

The concept of 'blockchain' is a notoriously difficult one to explain. Most attempts to encapsulate its essence seem to describe *what it does* rather than *what it is*. Most often, blockchain is characterized as the elements and methods enabling the creation of decentralized, distributed, and replicated digital ledgers. In computer science, blockchain systems are said to constitute distributed finite state machines—peer-to-peer networks capable of maintaining a single programmatic state across the entire network and its shared data, without any single participant having authority over another.

But none of that truly explains the blockchain phenomenon: what is blockchain and how does it fit in the bigger picture of digitalization. Without knowing what exactly one is looking at, it is difficult to observe the effects of a phenomenon on the socio-economic level. In other words, to perceive the effects of blockchain on digitalization, a well-structured and comprehensive socio-economic delineation of blockchain is required.

This constitutes the underlying thesis of this dissertation. It makes the case for a structured, comprehensive socio-economic delineation of blockchain systems as *multi-sided platforms*. Assuming a critical realist perspective, the dissertation focuses explicitly on the examination of the blockchain phenomenon in its original holotypic form of public permissionless blockchain systems. By doing so, it attempts to cut through the obfuscation inflicted by the hype and its diluted terminology in later years, and to reconstruct the story of the original blockchain phenomenon. What was it about, what happened to it, and what could it all mean for digitalization in the future?

1.2 Motivation for research

In recent years, the academic and professional discourse regarding blockchain technology have become increasingly redefined as discussion about *'distributed ledger technology'*, or *'DLT'*. The concept of distributed ledgers stemmed from the observation that public permissionless blockchain systems were poorly suited for implementation in enterprise value chains and company business processes. The alternative term allowed businesses to tap into the technology momentum while rejecting some of the more troublesome defining principles of the blockchain systems at the time.

Respectively, the use of the term 'blockchain platform' has started to rise in popularity in recent years. At the same time, the defining factors of what kinds of systems are included in these categorizations have become even more ambiguous. In fact, the holotype of a blockchain system has undergone almost a full reversal over the years. Systems now referred to as 'blockchain' would in many cases be categorically unsuitable to accomplish the tasks of the earliest manifestations of blockchain systems, and vice versa.

While the blockchain platform discussion seems to be largely dominated by distributed ledgers, blockchain systems adhering to the original public permissionless holotype have not disappeared entirely. The Bitcoin cryptocurrency network, for example, seems as vibrant and vital as ever before. Recently, public permissionless blockchain systems have also become increasingly associated with the discussion on the digital platform giants. For example, in October 2020, PayPal announced plans to integrate Bitcoin and other cryptocurrencies to its platform (BBC News, 2020b). Similarly, in 2019 Facebook announced plans to launch a permissioned blockchain cryptocurrency platform named Libra, with a roadmap to transition to a public permissionless blockchain architecture within a few years' time (BBC News, 2019; Libra Association, 2020). While Facebook has since dropped its plan for Libra's transition, initiatives such as these underscore the need for better delineation of the blockchain phenomenon (BBC News, 2020a).

The problem with how the blockchain discourse is becoming framed under the generic umbrella terms of distributed ledgers and blockchain platforms is that it obfuscates the differences in characteristics between public permissionless blockchain systems and the other entities included in these categorizations. To build a more comprehensive understanding of blockchain platforms and their impact on digitalization, the phenomenon needs to be investigated through a clearly delineated platform framework and with a commitment to a particular stream of platform research.

So far, public permissionless blockchains have not been comprehensively described as multi-sided platforms in academic discourse. Delineating the platform characteristics of public permissioned blockchain systems is important in order to establish whether permissionless and permissioned blockchains are different manifestations of the same phenomenon, or if they should in fact be recognized as two completely separate platform phenomena.

The underlying paradigms of how emerging technologies are perceived define how those technologies are developed and applied in society (Clark, Robert, & Hampton, 2016). Therefore, the underlying paradigms of the blockchain platform discussion must also be subjected to critical examination—otherwise society runs the risk of squandering its technological potential.

1.3 Research objectives and questions

The main objectives of this research are three-fold. Firstly, the dissertation makes an effort to describe the phenomenon of public permissionless blockchain systems as digital platforms. Specifically, the dissertation examines these systems from the perspective of the theory of multi-sided platforms.

Secondly, through this platform framework, this dissertation then seeks to understand the blockchain platform and the platform mechanisms therein. It especially examines the network dynamics, the value creation, the coordination mechanisms, and the resource allocation in such systems through a wide range of theoretical, methodological, and investigatory pluralism.

Thirdly, the dissertation then considers the combined effect of these factors to produce a synthesis of understanding on the transformative impact of public permissionless blockchain systems. In other words, the dissertation seeks to understand the ability or inability of blockchain systems as socio-technological compositions to instigate a disruptive reconfiguration of resources, markets, and other such factors of economic interaction in society that would alter the outcomes of interest for the parties involved. This transformative impact is especially elucidated in relation to the boundaries of the firm, the more conventional multi-sided platforms, and the digital platform economy in large.

To this end, this dissertation asks the following three main research questions:

1) *"How should blockchain systems be characterized in relation to the theory of multi-sided platforms?"*
2) *"How are the mechanisms in blockchain systems different from the earlier manifestations of their characterized ontology"*
3) *"What is the transformative impact of blockchain systems on the platform economy?"*

1.4 Contributions and value of the research

The findings of this dissertation indicate that public permissionless blockchain systems can be coherently described as multi-sided platforms. While significantly differing from contemporary multi-sided platforms in how costs, governance and incentivization are structured, blockchain systems exhibit all the makings of digital multi-sided platforms: the presence of multi-sided markets, the dependency on network effects, the emphasis on complementary assets, and the incentivization and control through technical and social boundary resources.

When observed through this lens, it seems that deep down at their core, blockchain systems can be characterized as *tools for network protocol permeation*. Translated into the vernacular of platforms, they constitute *an alternative method for deploying, growing and sustaining multi-sided platforms as ahierarchical peer-to-peer networks*. Contrary to contemporary platforms that typically require large initial investments to attract a critical mass of users, the initial cost of deploying a blockchain platform is typically very low. This eccentric growth dynamic enables a new kind of '*fire-and-forget*' approach to platform deployment—but with the trade-off of higher operating costs and platform resource scarcity.

Blockchain platforms are not to be taken as substitutes for conventional platforms, nor is their relevance to conventional business cases identical. Nonetheless, a synthesis of the research findings suggests that blockchain platforms are not completely void of a transformative impact on the platform economy. Instead, they pave the way for a potential transition from the contemporary service-structured view towards a more all-encompassing platform co-opetition and value co-creation perspective. Blockchain platforms can also enable new modalities of process automation in peer-to-peer settings, albeit with completely different kinds of structures of cost, governance, and incentivization than what are found in more conventional multi-sided platforms. Furthermore, the make-or-buy dynamics in blockchain platforms seem to oscillate independently from contemporary platforms, which can also have wider implications on the future development of the platform economy.

This research has several academic implications. Firstly, tying the phenomenon of public permissionless blockchain systems into the research stream of multi-sided platforms enables future studies to examine blockchain systems from a new powerful perspective. Perceiving blockchain systems as multi-sided platforms also helps to better understand their relation to the wider phenomenon of the digital platform economy and digitalization in general.

Secondly, the dissertation also has some implications on the theory of multi-sided platforms. During the research process, a completely new class of internal boundary resources was pinpointed in the operation of blockchain platforms, governing the interaction between individual providers of the same platform. Thus, the dissertation expands the notion of how platform collaboration can be arranged and in what kinds of configurations multi-sided platforms can exist.

Thirdly, the dissertation opens an avenue for further discussion on open source multi-sided platforms and platform co-opetition in peer-to-peer systems. Platform co-opetition has been a topic of interest in the academic discourse in recent years (Cohen & Zhang, 2016; Niculescu, Wu, & Xu, 2018; Yoo, Roh, Cho, & Yang, 2020). Understanding how blockchain platforms enable new modalities of platform co-opetition and value co-creation in peer-to-peer settings can improve the understanding on the future evolution of the platform economy in this regard.

Fourthly, in recent years, the blockchain discourse has become increasingly saturated with the logical fallacy of *argumentum ad decentralizationem,* so to speak—the notion that a decentralized system is inherently superior to a centralized one (Walch, 2019). The findings of this dissertation may enable better and more constructive critical examination of this decentralization paradigm in blockchain and DLT systems, as well as in platform configurations in general.

This dissertation also has practical implications for the business domain. By systemizing and solidifying the conceptual division between different types of blockchain systems in the platform domain, the dissertation helps businesses focus their strategic goals in a more meaningful manner, and to allocate their research and development efforts accordingly. An understanding of blockchain systems as an alternative method of deploying platforms can expand the innovation focus to also innovating around business processes that are not core to any of the participants involved.

1.5 Structure and the included articles

This dissertation is structured as follows. The first part of the dissertation contains the summary article. Section 1 of the summary features this introduction. Section 2 of the summary delineates the theoretical background regarding blockchain technology and multi-sided platforms. In Section 3, the methodological approach of each dissertation article is described and critically evaluated. Section 4 presents a summary of the findings of this dissertation. Finally, Section 5 concludes the summary with discussion on the findings.

Following the summary article, this dissertation comprises five included articles. Their contents can be briefly summarized as follows:

1) *Rajala, R., Hakanen, E., Mattila, J., Seppälä, T., & Westerlund, M. (2018). How Do Intelligent Goods Shape Closed-Loop Systems? California Management Review, Vol. 60(3), pp 1–25.*

The first article describes how disruptive decentralized technologies, such as blockchain systems and smart contracts, represent important infrastructural elements for collaboration and value creation in closed-loop ecosystems. The article discusses how blockchain-enabled smart contracts could be utilized to create self-reinforcing business models, enabling new kinds of platform integration for a circular economy.

2) *Mattila, J., Seppälä, T., Valkama, P., Hukkinen, T., Främling, K., & Holmström, J. (2021). Blockchain-Based Deployment of Product-Centric Information Systems. Computers in Industry, Vol. 125(2), 103342.*

Against the backdrop of product-centric information management literature, this article describes how blockchain systems may serve to alleviate hindrances in the integrational development of inter-industrial digitalization. By examining a blockchain-based participation protocol designed for product-centric data management, the article investigates whether by implementing blockchain smart contracts, a system-of-systems-level collaboration could manifest from a bottom-up approach through a network of incentivized protocols, rather than by a centrally driven top-down approach.

3) *Mattila J., & Seppälä T. (2018). Distributed Governance in Multi-Sided Platforms: A Conceptual Framework from Case: Bitcoin. In: Smedlund A., Lindblom A., Mitronen L. (eds) Collaborative Value Co-creation in the Platform Economy. Translational Systems Sciences, Vol 11. Springer, Singapore.*

In this article, blockchain architectures were analysed with the intent to determine whether they constitute multi-sided platforms as defined in academic platform literature. The paper also made an effort to delineate the internal and external governance and incentivization structures between the different market sides of such blockchain platforms. This analysis was performed by applying the platform governance framework of Tiwana (2014) to the case examination of the Bitcoin cryptocurrency network.

4) *Lauslahti K., Mattila J., Hukkinen T., & Seppälä T. (2018). Expanding the Platform: Smart Contracts as Boundary Resources. In: Smedlund A., Lindblom A., Mitronen L. (eds) Collaborative Value Co-creation in the Platform Economy. Translational Systems Sciences, Vol 11. Springer, Singapore.*

The basic premise of this article was to investigate whether blockchain smart contracts can constitute legal acts, with legally binding rights and obligations under the Finnish Contract Law. The article also looks at smart contracts from a platform boundary resource perspective. In other words, the article discusses whether smart contracts could be utilized to facilitate more dynamic and diverse boundary resources that lower the barriers of entry in platform settings even further than in contemporary platform configurations.

5) *Hukkinen, T., Mattila, J., Smolander, K., Seppälä, T., & Goodden, T. (2019). Skimping on Gas: Reducing Ethereum Transaction Costs in a Blockchain Electricity Market Application. Proceedings of the 52nd Hawaii International Conference on System Sciences.*

This article observes that ever since the 1980s, the evaluation of IT systems has not been based on their operating costs. Instead, the mainstream perception on IT systems has mostly viewed them as investments, mainly focusing on their effects and benefits over the entire lifecycle. To this end, the emphasis has been on infrastructures, human resources and intellectual property. The article demonstrates that as the computational resources of blockchain-based systems are offered on demand basis with allocation and pricing taking place according to free market mechanics, resource-efficiency and cost-optimization are placed at the centre of all application development. Delineating this focal readjustment, the paper describes how a new mode of thinking is required in software development for blockchain systems, with meticulous attention to computational efficiency.

2 Theoretical background

This dissertation employs two theoretical frameworks: the theory of multi-sided platforms, and the theory of transaction cost economics. This chapter introduces these theoretical frameworks and specifies to which schools of thought the dissertation subscribes within them.

2.1 Landscape of platform research

The concept of a platform is not an easy one to define accurately and exhaustively. The term is often casually used in business and policy discussions, with a broad spectrum of different kinds of meanings attached to it. Moreover, in academia, several streams of platform research have been conducted in separate research communities concurrently, making a uniform, all-encompassing definition an even more difficult one to formulate (Eloranta, 2016; Thomas, Autio, & Gann, 2014). Generally speaking, however, academic scholars across the board agree that the fundamental idea of platform thinking is to disentangle the static elements of an operation from the dynamic ones through various acts of modular design and architectural control, with the objectives of improved adaptability and control (Baldwin & Woodard, 2009; Boudreau, 2010; Parker, Van Alstyne, & Choudary, 2017). In other words, by applying carefully coordinated design rules to facilitate the integration of stable and dynamic elements, a higher degree of innovative dexterity is enabled in some areas while preserving economies of scale in others (Jacobides, Knudsen, & Augier, 2006; Teece, 1986; Thomas *et al.*, 2014).

In the earliest manifestation of platform research, engineers and scholars in the product innovation domain utilized the term 'platform' in an intra-firm context in reference to *product platforms*. This conceptualization referred to modular families of products which enabled economies of scale in production without sacrificing the customizability of product features (Meyer & Utterback, 1992; Wheelwright & Clark, 1992). Later on, in the realm of information systems research, this product platform mentality was extended to the examination of technology products and software (Bresnahan & Greenstein, 1999; Cusumano & Selby, 1995; Cusumano & Yoffie, 1998).

In an even more recent tangent, the same modular thinking has also been applied to *service platforms* in the fields of service marketing (Breidbach, Brodie, & Hollebeek, 2014; Ramaswamy, 2010; Sawhney, Verona, & Prandelli, 2005) and servitization (Brax & Jonsson, 2009; den Hertog, van der Aa, & de Jong, 2010; Kowalkowski, Witell, & Gustafsson, 2012). These research streams mainly view platforms as facilitators for service modularity, service logistics, and service innovation, often manifesting as digital environments of various kinds (Eloranta, 2016).

The term ‘platform’ has also been adopted into use in the realm of organizational research. Largely disconnected from the other streams of research, this academic convention mainly associates the term ‘platform’ with the more abstract concept of a *meta-organization*. These meta-organizational platforms are considered to comprise the core resources and competences of an organization which can be deployed in a modular fashion in any arrangement on an *ad hoc* basis, as warranted by the situation (Ciborra, 1996; Kim & Kogut, 1996).

2.2 Multi-sided platforms

In this dissertation, the term ‘platform’ is used explicitly in another meaning, differing from the ones above, and defined in the research stream of industrial economics and strategy. In this particular research tradition, the term ‘platform’ is used in reference to a *system of multi-sided markets*. With an architectural design of modular interfaces and boundary conditions, these systems enable various groups of actors (‘*market sides*’) to engage in value-adding activities together by interacting with each other through the system. In this context, a market is considered multi-sided if the outcomes of interest depend on more than one market side, and the system exhibits externalities in the form of indirect network effects (Boudreau & Hagiu, 2008; Eisenmann, Parker, & van Alstyne, 2006; Hagiu, 2014; Hagiu & Wright, 2015; Parker & van Alstyne, 2005; Parker *et al.*, 2017; Rochet & Tirole, 2003, 2006; Rysman, 2009).

Several delineations have been presented for multi-sided platforms over the past decades within this stream of research. One of the earliest conceptualizations emphasized the presence of *indirect network effects* between different groups of market participants. Network effects, in general, refer to a situation where the utility gained by a participant from using a system depends on the number of other participants also taking part in the same system. This dependency can either be positive or negative. *Direct network effects* take place when an increase in the use of a product or a service directly benefits or harms the users of that particular product or service in question. *Indirect network effects*, in turn, occur when an increase in the use of one product or service adds to or substracts from the value of using another product or service (Armstrong, 2006; Caillaud & Jullien, 2003; Katz & Shapiro, 1994).

Another commonly used characterization for multi-sided platforms which is closely related to indirect network effects is the presence of *complementarities*. Goods and services are considered complementary to one another if the utility they provide is higher when consumed together. As a classic example, a boat and two oars are more useful together than a boat without oars, or a pair of oars without a boat (Dahlander & Wallin, 2006; Gawer & Henderson, 2007; Teece, 1986; Yoffie & Kwak, 2006).

Platforms encourage the development of complementary assets by defining *boundary resources*. In the literature delineating multi-sided platforms, boundary resources are described as the operational guidelines and technical tools and interfaces governing the interactions between the platform provider and the platform participants. They can either be used to encourage innovation around the platform, or to restrict it—according to how much control the platform provider wishes to maintain over the developmental direction of the platform ecosystem (Baldwin & Woodard, 2009; Boudreau, 2010; Ghazawneh, 2012; Ghazawneh & Henfridsson, 2013; Yoo, Henfridsson, & Lyytinen, 2010).

Boundary resources can be divided into technical and social boundary resources. *Technical boundary resources* are associated with governing the technical interactions between the platform and its complementary constituents. They are often expressed in the forms of application programming interfaces (APIs) and software development kits (SDKs), for example. *Social boundary resources* form the framework for social interactions between the platform and its participants. To offer an example, these may include terms of agreement for application developers, or revenue split models determining how the added value generated via the platform is shared between the platform provider and the participants (Dahlander & Wallin, 2006; Gawer, 2009; Gawer & Henderson, 2007; Ghazawneh & Henfridsson, 2013; Teece, 1986; Yoffie & Kwak, 2006).

While fostering the growth of the platform, strong network effects also enable multi-sided platforms to generate a lock-in effect for their users by acting as a *bottleneck* between the market sides. In a lock-in situation, any user choosing to leave the platform must also forfeit the utility provided by the network effects of the platform. This bottleneck role and the resulting ability or inability for users to *multi-home*, so to speak, has also been offered as one delineating factor in multi-sided platform literature (Armstrong, 2006; Boudreau, 2010; Rochet & Tirole, 2003). Closely related to the bottleneck effect, characterizations have also been based on the gate-keeping which multi-sided platforms may exercise through their power to exclude users from the ecosystem. This power also grants the platform the ability to dictate terms of use, essentially rendering the platform provider a public regulator for the platform ecosystem (Boudreau & Hagiu, 2008; Cusumano & Yoffie, 1998; Jacobides *et al.*, 2006; van Alstyne, Parker, & Choudary, 2016). Thus, this mechanism has also been considered the basis for platform governance (Parker & Van Alstyne, 2014; Schilling, 2005; Tiwana, 2014).

Another proposal towards a definition for multi-sided platforms approaches the issue through competition and the pricing structure of the market. This approach underscores the fact that in multi-sided platforms, profits are not simply a product of costs and prices—but also a product of how those prices are allocated to different groups of market participants. By subsidizing one market side's participation, platforms can attract other more profitable market sides onboard through positive indirect network effects. This balancing between undercharging and overcharging different market sides and leveraging their network effects against one another is a key characteristic of the *modus operandi* of multi-sided platforms (Armstrong, 2006; Boudreau & Hagiu, 2008; Parker & van Alstyne, 2005; Rochet & Tirole, 2003, 2006; Rysman, 2009).

Multi-sided platforms can also be characterized in terms of fixed-role and switch-role market structures. Switch-role markets are ones where participants do not hold permanent roles as buyers or sellers. In other words, participants do not strictly identify with any particular market side. Conversely, fixed-role markets are ones where participants assume a permanent role and identify with one particular market side. Multi-sided platforms quintessentially exhibit a higher degree of switch-role markets than most conventional market environments (Aspers, 2007).

In a more recent delineation, Hagiu and Wright (2015) have argued that, in fact, a multi-sided platform should simply be understood as any system which enables direct interactions between multiple various market sides, each one of which is in some way associated with the system in question.

2.3 Transaction cost economics

Transaction cost economics emerged out of two complementary fields of economic research: new institutional economics (Coase, 1937, 1960; Commons, 1931; Williamson, 1979) and the new economics of organization (Day & Wendler, 1998; Moe, 1984, 1991; Yarbrough & Yarbrough, 1990). Unlike neo-classical economics which mainly perceives companies as technological production functions, transaction cost economics assumes a more organizational perspective to companies as governance structures (Williamson, 1998).

Institutional economics traditionally asks the question: “If there are markets, why are there companies?” (Coase, 1937, pp. 387–388; 1960, pp. 390). Along the same tangent, the key question in transaction cost economics could be formulated as: “If there are companies, why are they organized differently from one another?” (Williamson, 1979). The corresponding core claim in transaction cost economics is that companies attempt to handle their transactional relationships in ways which minimize their total costs of execution (Williamson, 1991). Consequently, to understand this company behaviour, transaction cost economics takes an interest in analysing how exactly those costs can be minimized. For instance, one archetypal problem around which a lot of this discussion is largely based is the so-called make-or-buy decision (Baker, Gibbons, & Murphy, 1997; Crawford, Klein, & Alchian, 1978; Grossman & Hart, 1986). This decision specifies whether a company chooses to manufacture a given product in-house, or to purchase it from an external supplier in an outsourcing manner.

Various categorizations have been suggested for transaction costs over the years. For example, in one of the earliest delineations, drawing directly from Coase’s work, Dahlman (1979) divides transaction costs into three categories: search and information costs, bargaining and decision costs, and policing and enforcement costs. In another proposition, North (1992) argues that transaction costs are in fact comprised of four variables: measurement, enforcement, market size, and ideological attitudes. Cheung (1992), in turn, argues that transaction costs are simply any costs which result from the involvement of institutions. In accordance with Cheung's interpretation, this dissertation assumes the view that internal organizational costs should also be included in the examination of transaction costs.

Human actors are viewed through lenses of bounded rationality and opportunism in transaction cost economics. In other words, the assumption herein is that individuals will always act out of self-interest, but with limited cognitive ability to do so (Dequech, 2006; Simon, 1985, p. 303). As a consequence, transaction cost economics predicts that complex contracts will always be unavoidably incomplete (Williamson, 1979).

2.4 Technical terminology and other key concepts

2.4.1 Blockchain technology, blockchain systems, and blockchain platforms

Blockchain-related terminology is not well defined in academic discourse (Mattila, 2016; Walch, 2017, 2019). However, the concept of a *blockchain* is generally associated with the information technology elements and methods enabling the creation of certain types of shared digital databases, often referred to as *ledgers*, and typically utilised to keep track of digital tokens of value, commonly referred to as *cryptocurrency* To this end, the entities in question quintessentially employ elements such as peer-to-peer networking, public-key cryptography, hashing algorithms, and a cryptographically concatenated append-only data structure (Mattila, 2016; Nakamoto, 2008).

The most likely origins of the word *blockchain* can be traced back to the beginnings of the Bitcoin cryptocurrency system: the white paper of Nakamoto (2008) and the Bitcoin source code. While there is no specific mention of the word 'blockchain' in Nakamoto's paper itself, the paper describes the underlying data structure of the Bitcoin system as a series of data blocks that are cryptographically concatenated into a virtual digital chain (Mattila, 2016).

Drawing from this supposed etymological origin, in the strictest sense, the term 'blockchain' refers to a type of an append-only data structure employed in systems such as the Bitcoin cryptocurrency network. However, as the database structure itself does not adequately describe the mechanisms that are required to maintain the database in a meaningful manner, the term *blockchain technology* quickly gained popularity. While anything but clearly defined at the time—or even still today for that matter—blockchain technology as a term could nonetheless be seen to encompass a larger construct. The concept quickly became associated with not only the blockchain database, but the entire technical complexity of how the provision and the maintenance of the database was orchestrated in order to provide qualities such as multi-version concurrency control, fault-tolerance, and immutability of record (Mattila, 2016).

In later years, the term ‘blockchain technology’ became corrupted in language, and simply referring to the entire technology composition as ‘blockchain’ became the dominant expression. Moreover, as the years progressed, the definition of ‘blockchain’ was diluted further, as an increasingly diverse variety of different kinds of systems started being labelled under the blockchain umbrella. Eventually, as a consequence of this trend of “*chainwashing*”, initiatives labelling themselves as blockchain projects did not necessarily share any notable similarity with the original holotypes but were simply seeking to nominally benefit from the hype phenomenon by other means (Swanson, 2017; Walch, 2017).

In academic literature, several defining characteristics have been put forward in attempts to delineate blockchain technology. Overwhelmingly, the most prominent feature in how the technology is described is its *decentralized* structure (Catalini & Gans, 2016; Walch, 2019; Yli-Huumo, Ko, Choi, Park, & Smolander, 2016). Due to the perceived lack of centrification, blockchain technology has also been prominently described as *trustless* or absent of trusted third parties (Glaser, Hawlitschek, & Notheisen, 2018). The technology has also widely been characterized as *immutable* and *transparent*, enabling cryptographic verifiability and non-repudiation (Conley, 2017; Koulu, 2016; Xu *et al.*, 2017).

In a computational sense, a blockchain network constitutes a distributed state machine: peer-to-peer networks capable of maintaining a single programmatic state—or consensus—across the entire network and its shared data, without any single participant having authority over another (Buterin, 2013; Shorish, 2018).

Due to its multi-level socio-technological perspective, this dissertation mainly perceives blockchain entities as *systems* rather than resorting to the more popular perspective of blockchain as a technology or an array of technologies. Hence, the dissertation resorts to the concept of *blockchain systems* with a larger emphasis on the incentives and the social human aspect, as well as the rules governing the interactions within and around that system. The dissertation also utilizes the term *blockchain platforms* in reference to blockchain systems which clearly exhibit the characteristics of multi-sided platforms, as described above in Section 2.2.

To elaborate, this dissertation defines blockchain systems as 1) open source and open access technology compositions; 2) comprising non-hierarchical peer-to-peer networks without any single points of failure or control; 3) which maintain consensus over cryptographically concatenated, shared and replicated append-only data structures; 4) according to deterministic self-contained consensus algorithms, void of external inputs such as validation by central authorities or off-chain signalling (Slootweg, 2016).

2.4.2 Smart contracts

In the early years of blockchain development, the main focus of application was on storing and transferring various kinds of assets and tokens of value in the blockchain systems. In other words, from the perspective of blockchain systems as distributed state machines, the variety of state transitions which the system could facilitate was relatively narrow and preordained. Relatively soon, however, a new trend in blockchain development started to emerge. This new approach placed more of an emphasis on the open configurability of the logic dictating how and when certain tokens in the system were transferred between accounts. By employing Turing-complete programming languages specifically developed for these systems, state-changing programs known as *smart contracts* could be created, stored and executed in the blockchain network in order to facilitate a multitude of versatile digital workflows (Buterin, 2013; Szabo, 1997; Wood, 2013).

In blockchain literature, smart contracts have been described as "programmatic containers for tokenized assets". Essentially, they are persistent computer programs which have the ability to autonomously govern crypto-tokens and to execute transactions to move them. Once a sum of tokens are deposited into a smart contract's address, they cannot be recuperated until the programming logic of the smart contract allows it. The smart contract itself is protected by the structure of the blockchain system: any attempt to tamper with the smart contract's logic is obvious, and easily rejected by the network (Hukkinen, Mattila, Smolander, Seppälä, & Goodden, 2019; Poon & Buterin, 2017; Wood, 2013).

By default, the environment for executing blockchain-based smart contracts is static and lifeless. In order to interact with the smart contract in a state-changing manner, the blockchain network must be compensated on a per-operational basis for providing service. These compensations also serve other functions in the system, such as allocating request priority, as well as deterring aberrant behaviour, such as requesting infinite computational loops. As every request to interact with the smart contract is bundled with its respective payment, any state-changing activities, such as database writes, are commonly referred to as *transactions* in the blockchain vernacular (Buterin, 2013; Glaser *et al.*, 2018; Mattila *et al.*, 2021).

In accordance with the definition drafted by Lauslahti *et al.* (2018), this dissertation defines smart contracts as digital computer programs that: 1) are written in computer code and formulated using programming languages; 2) are stored, executed and enforced by a distributed and replicated blockchain network; 3) can receive, store, and transfer digital assets of value; and 4) can execute with varying outcomes according to their specified internal logic (Lauslahti *et al.*, 2018).

2.4.3 Distributed ledgers

In recent years, the academic and professional discourse on blockchain has increasingly become redefined as discussion about *'distributed ledger technology'*, or *'DLT'*. The concept of distributed ledgers stemmed from the realization that public permissionless blockchain systems were poorly suited for implementation in enterprise value chains and company business processes. The alternative term allowed businesses to tap into the hype momentum while rejecting some of the more troublesome defining principles of blockchain systems as well as the highly questionable reputation of cryptocurrencies at the time.

Several fundamental differences can be pinpointed between the definitions of blockchain systems and distributed ledgers, as interpreted by this dissertation. Firstly, DLT systems are not necessarily built in accordance with open-source principles and may involve proprietary software code not accessible to the general public. As such, they do not necessarily conform to the idea of 'the right to fork code'—a pivotal mechanism and a fundamental paradigm in open-source development (see Section 4.3.2) (De Filippi & Loveluck, 2016).

Secondly, DLT systems do not necessarily represent ahierarchical peer-to-peer network topology. In other words, unlike in blockchain systems, all participants are not necessarily equally privileged, but may be organized into various types of hierarchies instead. Consequently, DLT systems may not be open to all willing participants to partake but a permission by a system authority may be required instead. In other words, as a deviation from *permissionless* blockchain systems, DLT systems may be *permissioned* in terms of accessibility by the general public (Glaser *et al.*, 2018).

Thirdly, DLT systems do not necessarily utilize the blockchain-like append-only data structure of cryptographically concatenated blocks of data. Respectively, the same applies to the entire technical complexity of how the provision and maintenance of such blockchain-like databases is configured to provide multi-version concurrency control, fault-tolerance, and immutability of record (Glaser *et al.*, 2018; Mattila *et al.*, 2019).

Fourthly, by extension from the previous point, systems which fall into the DLT category do not necessarily involve a protocol-level incentivization mechanism for participating and collaborating with the system. Thus, DLT systems do not necessarily employ cryptographic tokens of value in a similar fashion as blockchain systems to keep the system intact and operational (Catalini & Gans, 2016; Glaser *et al.*, 2018; Mattila *et al.*, 2019)

To summarize, while the terminology remains somewhat ambiguous, this dissertation interprets 'distributed ledger' as a more loosely defined, wider concept in comparison to 'blockchain'. As such, it is placed somewhere between blockchain systems and the more generic phenomenon of data systems integration in digitalization. While delineating the differences between blockchain systems and DLT systems is relatively straightforward from this perspective, it may in fact be more difficult to differentiate between distributed ledgers and ordinary IT system integration pertaining to digitalization in some cases. Nonetheless, for the intents and purposes of this dissertation, it can be stated that while DLT systems typically exhibit *some* properties of blockchain systems, they do not, by definition, exhibit *all* of them.

2.5 Blockchain platforms in prior literature

While blockchain systems have not been comprehensively described as platforms in academic literature, some early considerations regarding their platform-like nature have been presented. While the descriptions are mostly concise and clearly not the focal point of these studies, many earlier discussions in the literature seem to lend credence to the view that blockchain systems can be delineated as multi-sided platforms.

For example, relatively early on in the emergence of the stream of blockchain literature, Böhme, Christin, Edelman, & Moore (2015) have taken notice of the Bitcoin cryptocurrency system's platform-like nature. In its description, the paper emphasizes the role of the market incentives in building a critical mass for the system, more or less in accordance with the idea of multi-sided platforms fostering network effects through boundary resources and joint revenue models.

Catalini & Gans (2016) briefly describes the Bitcoin cryptocurrency system as a *decentralized market* enabled by an open protocol, which may be utilized as a *development platform* for novel applications. While at first glance, the description could be seen to support the idea of a digital service platform or a software platform in the product platform stream of literature, the paper in fact mainly discusses the Bitcoin cryptocurrency system from the perspective of markets and market design, firmly anchoring it in the multi-sided platform domain.

Similarly, Athey, Parashkevov, Sarukkai, & Xia (2016) defines the Bitcoin cryptocurrency system as an open-source *technology platform* enabling the creation of a variety of services by independent developers. While initially the paper may give the impression of subscribing to the concept of a digital service platform or a software platform, the caveat is in fact offered by the authors that the focus of the paper is not on the platform perspective, but rather on the market-related aspects of the system, such as price formation and user adoption.

Respectively, Conley (2017) remarks that blockchain technology is mainly used to *intermediate new markets or make existing markets more efficien*t, with "significant network externalities". Furthermore, the paper makes several comments reflecting the idea of the key role of crypto-tokens having to do with incentivizing platform deployment and its growth. For example, the paper points out that while the revenue sharing rules related to crypto-tokens are not always clear, they play a wide variety of roles in the system, also having turned out a very effective way for start-ups to raise early funding. In another example, while highlighting certain discrepancies in the funding mechanism and the pricing of the tokens, Conley makes an indirect reference to the link between crypto-token funding and platform development:

> *"Burdening tokens with duties decreases their value. It is not clear that this is a good strategy for a start-up. The services of token holders will all be provided in the future after the platform is launched and becomes established. However, the present value of the cost of these services gets deducted from the tokens at the time of the ICO. This is like a start-up paying its expected electricity bill 20 years in advance instead of using the money to develop the platform more quickly."*

Perhaps one of the most comprehensive discussions on blockchain systems as multi-sided platforms, however, can be credited to Glaser, Hawlitschek, & Notheisen, (2019) in earlier literature. Clearly subscribing to the multi-sided market perspective on platforms, the paper explicitly expresses the view that "blockchains are open platforms, and therefore research on and knowledge about digital platforms and blockchain share a common ground". Assuming a socio-technical perspective, the paper briefly addresses the technical differences in the characteristics of incumbent digital platforms and blockchain platforms. However, as the paper then mainly focuses on examining the institutional aspects of blockchain platforms and their implications to platform governance, its delineation of blockchain platforms remains limited in scope and incomprehensive regarding multi-sided platform literature and the platform characteristics thereof.

In addition to the examples discussed above, the term 'blockchain platform' has been used in many contexts in reference to more broadly defined DLT systems (*e.g.* Sousa, Bessani, & Vukolic, 2018). However, as these instances fall outside of the scope and the focal point of this dissertation, more detailed discussion regarding these studies is omitted.

3 Methodology

3.1 Research design

3.1.1 Methodological positioning

Methodologically, this dissertation positions itself in the domain of *critical realism*. Born out of Roy Bhaskar's seminal works on transcendental realism (Bhaskar, 1975) and critical naturalism (Bhaskar, 1978, 1979), critical realism emerged as a response to the need to mitigate the challenges of both the positivist dogma dominant at the time, and the post-structuralist linguistic turn in social sciences (Geary, 2016; Mingers, Mutch, & Willcocks, 2013).

From an ontological perspective, critical realism subscribes to *ontological realism*. Consequentially, the dissertation makes a distinction between the objective reality and that which is observable. In detail, critical realism differentiates between three levels of ontological stratification: the *real* (the things, structures and causalities that are), the *actual* (the events that happen), and the *empirical* (the observations through which events are perceived and experienced). In other words, while the structure of reality is considered intransitive—*i.e.* existing independently from human perception—the view is that it can only be perceived through the observable events which manifest from that underlying structure (Bhaskar, 1975; Mingers *et al.*, 2013; Sorrell, 2018). Thus, this dissertation makes the concession that while certain structures and causalities may exist, they might never manifest themselves in the form of observable events—and even when they do, those events might never be successfully observed (Archer *et al.*, 2016).

The epistemological commitment in which critical realism is rooted is *epistemic relativism*. In other words, even though observable events may emerge from the structures and causalities of reality, they can never be observed *objectively*. Instead, critical realism stipulates that these observations are always experienced through factors such as culture, social context, history, and the limitations of human perception. (Archer *et al.*, 2016; Bhaskar, 1975; Sorrell, 2018) This notion of fallibilism is also reflected in the research design of this dissertation.

Due to its chosen combination of ontological and epistemological commitments, critical realism holds a view of *judgemental rationality*. In other words, due to the intransitive nature of reality and the subjective nature of observation, critical realism stipulates that it must be possible to make the distinction of which accounts of reality are better than others. Consequently, values—insofar as they are rooted in reality—are also considered subject to empirical critical evaluation (Archer *et al.*, 2016; Bhaskar, 1975; Sorrell, 2018). Due to this disposition of *ethical naturalism* embedded in the critical realist approach, this dissertation considers it possible to distinguish between good and bad reactive outcomes for society, and therefore, managerial and policy implications can also be formulated on the basis of the research findings (Sayer, 1997).

3.1.2 Units of analysis and observation

The unit of analysis in this dissertation is a multi-sided platform. This unit of analysis is observed through a multi-level perspective on socio-technological systems (Sorrell, 2018). Consequently, in the included articles this unit of analysis is broken down into two basic layers of interest: 1) the technological platform system, and the laws and principles guiding its operation; and 2) the network of humans and human interactions, and the social constructs determining their behaviour within and around the technological platform system.

On the two levels of interest specified above, the included articles look at the unit of analysis from various different perspectives: business models and value creation, power structures and governance, incentivization and growth, interaction and contractual mechanisms, as well as operational efficiency. Each one of these perspectives focuses on their own specific units of observation (*"the empirical"*), depending on the things, structures and causalities they are trying to capture (*"the real"*) and according to the events which are of interest for that specific viewpoint (*"the actual"*).

The perspective of *business models and value creation* focuses on understanding how participants can interact with each other within and around the blockchain platform domain in order to add and capture value. So far, few proven business use cases have been documented in the context of blockchain platforms (Burg, Murphy, & Pétraud, 2018). The units of observation for this perspective consist of conceptual design proposals and simulations, and the mechanisms of added value and monetization thereof.

The perspective of *power structures and governance* looks at the interlink between the governance of the technological system and the coordination of the human behaviour within and around it. For this particular perspective, the units of observation are the dependencies between the participating market sides on one another. They are expressed through a bi-directional influence between the two layers of interest:, namely the technological system affecting the human behaviour ("governance *by* the platform"), and the human behaviour affecting the configuration of the technological system ("governance *of* the platform") (De Filippi & Loveluck, 2016; Tiwana, 2014).

The perspective of *incentivization and growth* focuses on delineating how blockchain platforms algorithmically balance and align the incentives of the various market sides to instigate participation. The units of observation examined by this perspective are the game-theoretical settings of how the collaboration between the participating market sides is compensated, and how those compensations are aligned to foster a positive feedback loop of growing indirect network effects.

The perspective of *interaction and contractual mechanisms* explores how the technological underpinnings of blockchain platforms facilitate ahierarchical yet binding arrangements between human participants, and whether those arrangements carry the same legal effects as legal contracts in the conventional platform domain. The perspective also examines how blockchain systems enable the use of open incentive structures and algorithmic enforcement of software code execution in lieu of contractual agreements and court proceedings. The unit of observation used for this perspective is the programmatic code of blockchain smart contracts and their alignment with the contractual mechanisms and coercive means of the legal tradition in the Nordic countries.

The perspective of *operational efficiency* examines the viability of blockchain platforms to function as a basis for social human interaction from the standpoint of costs of operation. In this respect, the units of observation include factors such as costs of computing and other IT resources, transaction costs and their volatility and predictability, as well as the general cost efficiency of the underlying technological system in comparison to more conventional solutions.

3.1.3 Research process

In the beginning of the research process, the maturity of blockchain technology was still in its early infancy. In fact, very few had ever even come across the term 'blockchain'. Moreover, even amongst the companies working directly with the technology, value-adding business applications with proven sales were extremely few and far in between. Conceptual ideas for use cases were readily available on the Internet, but mostly these ideas had not been properly documented or evaluated with any scientific rigor. Likewise, the field of research around the phenomenon was only just beginning to emerge. Systematic theoretical frameworks describing blockchain systems had not yet been established as the basis of academic research. For these reasons, exploratory and explanatory research approaches were called for at the time.

As its primary objective, this dissertation set out to describe, to delineate, and to understand the phenomenon of blockchain networks as techno-socio-economic systems. To this end, the dissertation, as a whole, employed an overspanning critical realist approach in its effort to answer the three main research questions. In other words, while the included articles employed varying individual research methods, through their observations, findings and conclusions they contributed to the overspanning retroductive process. In this regard, critical realism was considered a well suited methodological positioning for this dissertation because the overall aim was not to predict, or to interpret the phenomenon—but rather to *explain* it (Sorrell, 2018).

In its pursuit for knowledge, critical realism mainly resorts to *retroduction*, rather than taking the more conventional avenues of deduction and induction. The process of retroductive reasoning begins with *empirical observation*. The observations are then utilized as the basis for forming *hypotheses* on what kinds of a mechanisms could generate the observed empirics. Then, in a retrofitting manner, critical realism attempts to *analyse* which mechanisms best describe the necessary conditions for the original observations to emerge. On the basis of the findings of these analyses, *conclusions* can then be drawn regarding the nature of the phenomenon (Bhaskar, 2014; Mingers, 2004).

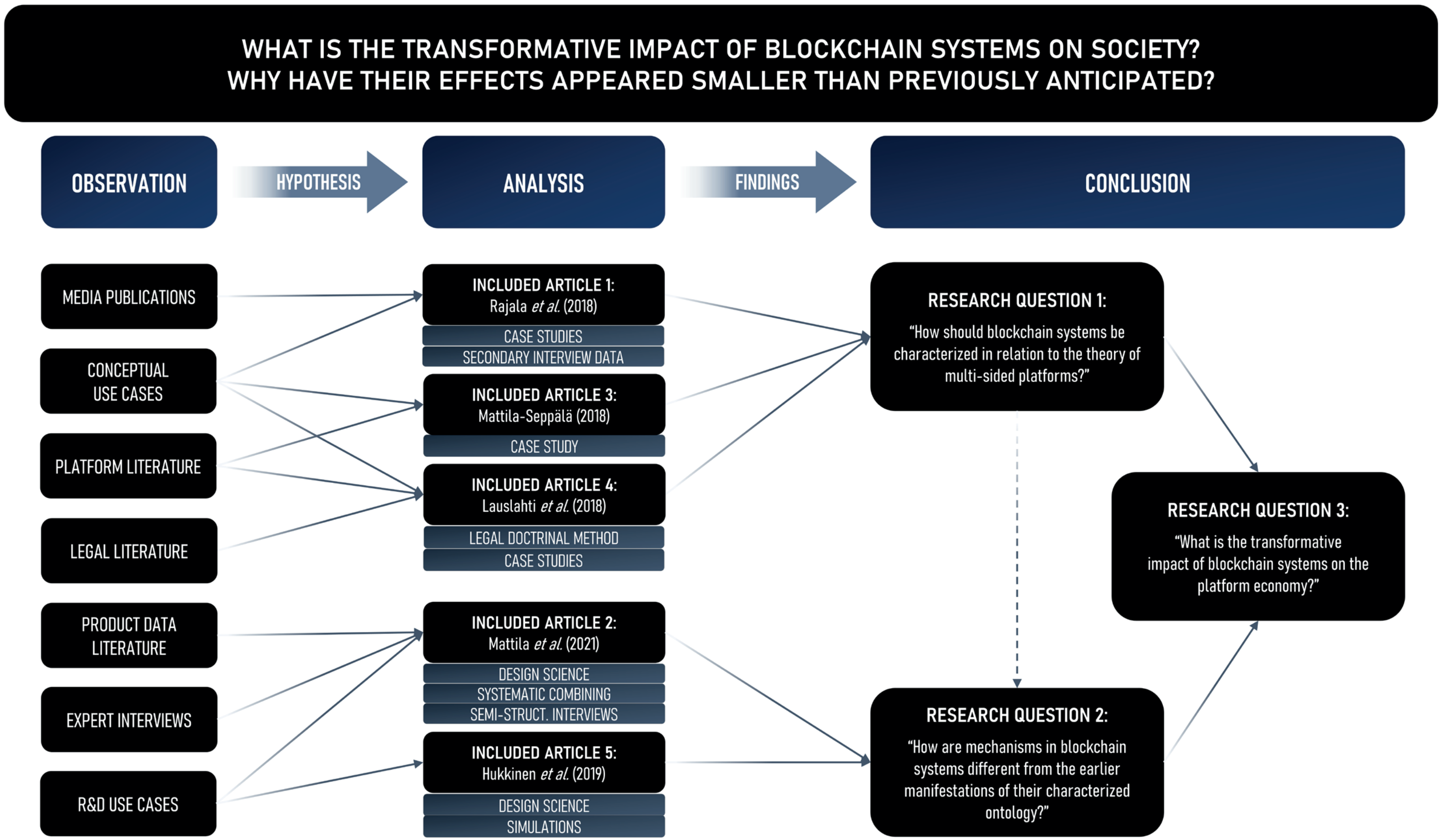
Following the form of a retroductive research process in critical realism, this entire body of work was based on a research design involving three overlapping main phases to which the individual articles were subjugated and contributed via a plurality of individual research methods (see Figure 1). In the observation phase, general observational data was gathered with the aim of establishing a preliminary understanding on the nature of the research phenomenon. In order to acquire first-hand insight on the development of blockchain technology, several visits were conducted to the global innovation hubs of blockchain technology (*e.g.* Berlin & the Silicon Valley) early on in the research process. During these excursions, several unstructured background interviews were conducted with high-profile technology experts (*e.g.* Stu Feldman & Jed McCaleb), and research visits were made to several prominent blockchain companies at the time (*e.g.* 21 Inc., Eris Industries, and Ascribe).

Due to the lack of rigorously documented and publicly available use cases, this research phase also involved research and development collaboration with some Finnish large-scale companies (*e.g.* Fortum Oyj, Euroclear Finland Oy). The purpose of these exploratory joint research ventures was to design, document, evaluate, and publish exploratory R&D use cases in various sectors of society, *e.g.* the energy industry and the financial sector.

From the various forms of initial observation, including unstructured expert interviews, conceptual use cases, media publications, and several streams of academic literature, the critical realist hypothesis was formed that the theory of multi-sided platforms developed by industrial economists may offer a clear, consistent, and versatile framework for delineating blockchain systems. One of the key aspects of the multi-sided platform perspective which motivated this hypothesis was its emphasis on network effects. This focal point quickly enabled a more thorough understanding on the dynamics of blockchain networks and their growth. Furthermore, the concept of boundary resources in the multi-sided platform literature seemed to offer a powerful tool for potentially explaining the complex interaction dynamics and incentivization mechanisms by which these networks emerge and evolve.

In the analysis phase, the initial observations and the synthesized hypothesis were utilized as the basis for the more refined research objectives in the included articles. Corresponding to the perspectives delineated in section 3.1.2, these research objectives were aimed at testing various aspects of the critical realist multi-sided platform hypothesis for blockchain systems, and they were pursued with a plurality of differ-

Figure 1. A flowchart describing how the main research questions of this dissertation were addressed through an overarching retroductive research process.



ent methods and author collaboration. Concurrently, these objectives in the analysis phase involved theoretical development in the form of conceptual delineation, the classifying of technical taxonomies, and the bridging of various theories and research conventions in order to provide an thorough academic framework for the main hypothesis, also to be utilizable in further studies.

Progressing to the conclusion phase of the critical realist research process, the results of the work conducted for the included articles in the analysis phase were synthesized to formulate the primary research findings of this dissertation. With the help of these findings, an effort was then made to provide answers to the three main research questions of this dissertation and to verify the multi-sided platform hypothesis.

3.1.4 Methods and data

Due to the exploratory and explanatory approach, the research process for this dissertation involved a fair degree of methodological pluralism. Overall, the dissertation comprised qualitative, quantitative, design-based, and legal research methods. Consequently, several various kinds of data were also used in the articles included in this dissertation, comprising both primary and secondary sources, *e.g.* literary sources, simulations, interviews, and software code (see Table 1). For the most part, the included articles comprised qualitative and design-based research methods.

Case studies. The most prominent qualitative method used in the included articles was case study research (see *e.g.* Jocher, 1928; Stake, 1978). In the included article #1, three hypothesis-generating case studies were conducted in three areas. The first case (reported in article #1) is an empirical study of a metal manufacturer, the analysis of which was based on 35 interviews conducted over a period of almost two years, from spring 2014 to the end of the year 2015. The interviews were voice recorded and subsequently transcribed verbatim. The second case (in article #1) focused on analyzing the multi-sided platform of a waste management company. The data for this case consisted of publicly available interviews with company executives, brochures, marketing materials and other secondary documents available from the company, including annual reports, bulletins, presentations, reviews, web sites, as well as reports produced by industry associations and trade magazines. This extensive set of secondary data provided an opportunity to analyse the case from the perspective of this dissertation. The third case (in article #1) reports a conceptualization of an industry platform in the automotive battery industry. The analysis in this case was based on data collected from media publications, unstructured expert interviews with managers and experts in the energy industry, and pre-existing published use cases in the battery industry. The data was complemented with research reports from earlier exploratory studies (Mattila & Seppälä, 2015). The three cases were then analysed in a heuristic manner and compared with publicly available secondary interview data to create propositions regarding how disruptive technologies can increase the intelligence of goods and revitalize business models in the circular economy.

In the included article #3, the case study method was used for a plausibility probe in analysing the multi-sided platform hypothesis of blockchain systems. To this end, secondary empirical data on the Bitcoin cryptocurrency system found in extant research literature was analysed and compared to academic literature on multi-sided platform characteristics. Furthermore, the extant literature was also analysed in an effort to delineate the distributed governance structure of blockchain platforms. This part of the data analysis followed the structure of the platform governance framework delineated by Tiwana (2014).

The included article #4, in turn, utilized three conceptual case studies in a theory-testing manner to determine if and by what conditions smart contracts can constitute legal contracts (Bennett, 2004; George & Bennett, 2005). The data sources and the principles of data analysis for this article are discussed further along in this section in the context of the Nordic legal doctrinal method.

Semi-structured interviews. The included article #2 also involved the use of semi-structured interviews (Harrell & Bradley, 2009). In essence, the semi-structured interviewing method was used to evaluate key assumptions and concepts regarding a proposed design artifact, and to map the interviewees' views on critical issues regarding the implementability of the solution in the problem domain. For these interviews, the interviewees were chosen using opportunistic selective sampling (*i.e.* convenience sampling) where interviewees were targeted based on their availability and heuristically evaluated ability to contribute valuable insights to the study. The interviews took place between December 2019 and September 2020. All semi-structured interviews were recorded, transcribed using artificial-intelligence-based speech recognition and human verification, and manually coded and analysed for key insights.

Simulations. In article #5, simulations were utilized to evaluate the operating costs of executing smart contract programs in the Ethereum blockchain. To this end, a local instance of TestRPC version 6.0.1 was run on an Ubuntu 16.04.3 LTS machine to simulate an Ethereum blockchain. In this simulated instance, data was collected by calling a function to perform an evaluation measurement on the required resource consumption of performing a given transaction in the canonical blockchain. The data was then quantitatively analysed to determine the operating costs of various smart contract structures, and the efficacy of the optimization process.

Design science. In addition to the purely qualitative and quantitative methods described above, design-based research methods were also utilized during the research process. Article #2 employed design science to explore whether a product-centric data system could be established according to a novel design principle placing successful deployment and inter-industrial scope as the main design priorities. An exploratory design artifact was drafted based on a smart contract developed for a tentative conceptualization earlier in the observation phase. Set in the context of the property market, apartments as capital goods, and transactions of shares of stock in housing companies as information workflow processes, this original conceptualization served as an initial exploration on the potential of blockchain systems in industrial applications. To that end, the original conceptualization made an effort to shed light on whether blockchain systems could be used to create a distributed coordination and data management architecture for decentralized workflows in the real estate market, in accordance with the product-centric information management approach (Hukkinen, Mattila, & Seppälä, 2017). In article #2, this exploratory smart contract was iteratively refined, contextualized to a more relevant product item example and industry setting, and evaluated for validity and further insight.

Respectively, the included article #5 employed design science to investigate whether the problem of high transaction costs in blockchain-based smart contracts could be alleviated through a variety of optimizing principles. Like in article #2, the design artifact in article #5 was also based on an earlier exploratory R&D use case developed in the observation phase of this dissertation. This original R&D use case involved a smart contract focused on exploring whether autonomous machine-to-machine transactions of electricity could be facilitated by blockchain smart contract in a housing society environment (Hukkinen, Mattila, Ilomäki, & Seppälä, 2017; Mattila *et al.*, 2016). In article #5, this exploratory smart contract was refined further and optimized in an attempt to improve its operational efficiency.

Multiple various definitions have been presented for design science in the academic literature. Thus, it should be noted that the design science approaches utilized in the included articles #2 and #5 in this dissertation represent differening academic dispositions in this regard. Article #2 mainly subscribes to the idea of design science as *exploration through design* (Holmström, Ketokivi, & Hameri, 2009). Thus, the article does not fully adhere to the guidelines of Hevner & Chatterjee (2010), for example, nor the principles, practices, and procedures of Peffers, Tuunanen, Rothenberger, & Chatterjee (2008) on design science as *artifact creation and evaluation*. Article #5, however, makes a more steadfast commitment to design science as the *creation and evaluation of innovative IT design artifacts* in accordance with strict principles, as outlined by Peffers *et al.* (2008). Furthermore, neither one of the articles in question reflects the idea of design science as *the study of design processes* (Aken & van Aken, 2013).

Systematic combining. In the include article #2, systematic combining was also used as a supportive method for new practice design (Dubois & Gadde, 2002, 2014). In order to establish the design principles and to refine the exploratory design artifact accordingly, the study employed systematic combining by engaging in iterative search heuristics via emergent theoretical framework development, empirical fieldwork, drafting of a practical demonstration, and evaluating the problem domain in a somewhat overlapping manner, based on the larger retroductive hypothesis of this dissertation.

Table 1. A methodological description of the included articles.

	ARTICLE 1	ARTICLE 2	ARTICLE 3	ARTICLE 4	ARTICLE 5
CITATION	Rajala et al. (2018)	Mattila et al.(2021)	Mattila–Seppälä (2018)	Lauslahti et al. (2018)	Hukkinen et al. (2019)
RESEARCH QUESTION(S)	▪ How does the increase of intelligence in goods influence the sustainability of industrial closed-loop ecosystems?	▪ How to establish a product-centric information management system which is viable for cross-industrial system-of-systems-level deployment and sustained existence?	▪ Are blockchain architectures compatible with the framework of multi-sided platforms? ▪ What kinds of platform governance structures do blockchain architectures exhibit?	▪ Can smart contracts be used to perform legal acts under Finnish contract law?	▪ How to improve the efficiency of a smart contract designed for microtransactions of electricity in a nanogrid environment?
RESEARCH APPROACH	▪ Conceptual	▪ Conceptual ▪ Empirical	▪ Conceptual	▪ Conceptual ▪ Legal doctrinal	▪ Empirical
THEORETICAL BACKGROUND	▪ Theory of multi-sided platforms	▪ Theory of multi-sided platforms	▪ Theory of multi-sided platforms	▪ Theory of multi-sided platforms	▪ Transaction cost theory
UNIT OF ANALYSIS	▪ Industrial ecosystem	▪ Multi-sided platform	▪ Multi-sided platform	▪ Smart contract	▪ Smart contract
RESEARCH METHODS	▪ Case studies ▪ Secondary interviews	▪ Design science ▪ Systematic combining ▪ Semi-structured interviews	▪ Case study	▪ Nordic legal doctrinal method ▪ Case studies	▪ Design science ▪ Simulation
DATA SOURCES	▪ Academic literature ▪ Secondary interviews ▪ Conceptual use cases	▪ Academic literature ▪ Conceptual and R&D use cases ▪ Semi-structured interviews	▪ Academic literature ▪ Secondary empirical evidence	▪ Academic literature ▪ Conceptual use cases	▪ R&D use case ▪ Simulation data
KEY RESULTS AND INSIGHTS	▪ Establishes decentralized technologies as important infrastructural elements for collaboration and value creation in closed-loop ecosystems. ▪ Describes how smart contracts could be utilized to create self-reinforcing business models and new kinds of platform integration.	▪ Delineates blockchain systems as tools for network deployment and growth ▪ Points out the need for a new design mentality where design priority is placed on successful system-of-systems-level deployment and cross-industrial scope	▪ Establishes blockchain systems as multi-sided platforms ▪ Delineates basic platform market side dynamics and incentivization mechanisms in blockchain systems	▪ Establishes smart contracts as platform boundary resources ▪ Delineates individual interaction dynamics and incentivization mechanisms in blockchain systems ▪ Presents the idea of social boundary resources as technical enablers	▪ Points out the need for a new design mentality with an emphasis on IT system efficiency ▪ Establishes universal optimization principles for smart contract development ▪ Delineates the problematic cost structure of blockchain systems

Legal dogmatics. As a slightly more idiosyncratic outlier, the Nordic legal doctrinal method was also employed in one of the included articles (Aarnio, 1977, 1978; Hirvonen, 2011; Timonen, 1998). Legal doctrinal research, also sometimes referred to as *legal dogmatics*, attempts to study the state of the law as it currently stands (Hirvonen, 2011). In this method, legislation, established custom, legislative drafts, court decisions and other permissible jurisprudential research material are analysed in a strictly hierarchical manner to make legal determinations regarding current legal norms (Raitio, 2012). In other words, legal dogmatics holds the view that the status of a certain invididual's rights and obligations, for example, can be determined by hermeneutically examining and interpreting those sources of material which are allowed and required to be taken into account. In this hermeneutical interpretation, deciphering the meaning of a text is considered to be a circular process between the collective and its individual parts. In other words, in the view of hermeneutics, the meaning of any given part of text cannot be understood without references to its other parts (see *e.g.* Jørgensen, 1957).

In this dissertation, the legal doctrinal method was used to determine whether blockchain-based smart contracts can in fact constitute legal acts. In other words, the emphasis was on evaluating how the legal principles found in the Finnish legal system regarding contract formation are applicable to blockchain-based smart contracts. To this end, through explorative case analyses on Ethereum smart contract programming code drafted by the authors, the paper applied the strict hierarchical interpretation hermeneutics of the permissible jurisprudential material in the Finnish legal system to evaluate whether the requirements for establishing a legal contract can be programmed into blockchain-based smart contracts.

3.1.5 Triangulation

Triangulating is a useful practice in business and social science research. In some cases, the use of triangulation can either validate or challenge earlier research findings (Campbell & Fiske, 1959). In other cases, triangulation can offer extended insight into the research problem by providing an alternative perspective on the matter (Carvalho & White, 1997; Turner & Turner, 2009). Three types of triangulation were utilized in the included articles: methodological, investigatory, and theoretical.

Methodological triangulation was employed by utilizing a multitude of research methods in the research process, representing both qualitative and quantitative approaches. Methodological triangulation offers a powerful tool for cross-check the validity of one's findings by leveraging the strengths of various different research methods against one another, thereby making up for the weaknesses of individual methods (Turner & Turner, 2009).

Investigatory triangulation was utilized in the sense that each one of the included articles involved collaboration with a different group of authors. With investigatory triangulation, a wider range of specialization and deep expertise can be leveraged to produce more detailed and meaningful insights on the phenomenon, with better understanding of the context relevant to each perspective. Considering the viewpoint of epistemic relativism to which this dissertation subscribes, involving a variety of investigators also improves the chances of dissipating the effect of any subjective observational filters which any of the individual authors might have (Turner & Turner, 2009).

Theoretical triangulation was also exploited in the form of theoretical pluralism. In practice, this was done by drawing theoretical insight from two theoretical frameworks: the theory multi-sided platforms, and the theory of transaction cost economics. Individual papers also partially resorted to drawing insights from other theoretical research conventions, such as the theory of the digital twin and cyber-physical systems. The included articles also contained some conceptual research, with the specific aim of bridging theories, pointing out new relationships of interest, improving theoretical coherence of the phenomenon of interest, and proposing new directions and perspectives for future research (Bechara & Van de Ven, 2011).

3.2 Critical evaluation

3.2.1 Critical evaluation of methodological positioning

Critical realism was chosen as the methodological approach because it provides an alternative to the positivist paradigm and its emphasis on universal laws, regularities, and regression-based models—but without sacrificing causality and explanatory research goals completely for the benefit of hermeneutic analyses and interpretation, like in the case of postmodernism, for example (Archer *et al.*, 2016; Gorski, 2013). Furthermore, the positivist approach was not deemed suitable due to the early stages of theory building and construct development around the blockchain phenomenon. Respectively, the constructivist paradigm was rejected due to the fact that even after a decade of development, no well-structured nomenclature has been successfully defined for blockchain research, and no clear consensus even exists on how the term 'blockchain' should be defined in the first place. Thus, as a methodological choice, critical realism was deemed particularly well suited for this dissertation where the aim is not to predict, or to interpret—but rather to *explain* (Sorrell, 2018).

In more scientific terms, rather than resorting to deduction or induction in its pursuit for knowledge, critical realism mainly engages in *retroduction*. On the basis of empirical observation, it hypothesizes what kind of a mechanism could generate that observation. Then, in a retrofitting manner, so to speak, critical realism makes the effort to select the mechanism which best describes the necessary conditions for the observation in question to emerge (Bhaskar, 2014; Mingers, 2004). However, herein lies the first pitfall of critical realism: one must be cautious not to venture too far into the retroductive explanatory realm. Often, the temptation is to build an explanatory model of the phenomenon which is more and more versatile, eventually becoming almost universally applicable to the point of impossible falsifiability. Thus, for the methodological foundation of the research, it is important that the comparative endeavour between different hypothesized frameworks is not entirely neglected (cf. Sorrell, 2018).

To avoid this pitfall of overly versatile explanatory frameworks lacking a comparative dimension, the research design for this dissertation involved an effort to incorporate a slightly different explanatory framework in each one of the included articles. From a critical standpoint, it is noteworthy, however, that these incorporated frameworks do not completely overlap with one another in the phenomenal research domain. Therefore, the comparative dimension of this dissertation is not as strong as it could be. However, by making this conscious choice of partially offsetting the explanatory frameworks, a more diverse understanding of the examined phenomenon is enabled on a much deeper level, therefore arguably making the tradeoff more than justifiable.

From the point of view of this dissertation, another weakness of the critical realist approach stems from its steadfast commitment to ontological realism. As the linguistic turn critics of critical realism have astutely argued, concepts may inherently be a subjective social phenomenon—that is, they may be irreducibly manifested in human language (Potter, 2003). Should this be the case, whatever assertions are made regarding *"the real"* will always be conceptually bound and distorted. This, in turn, would stand in direct contradiction to the position of ethical naturalism to which critical realism and this dissertation subscribe. In other words, critical realism may be over-confident in its ability to produce actionable practical advice by answering questions regarding values, desirability of outcomes, and that what ought to be (Dobson, 2005; Sayer, 1997). Due to the pragmatic aspiration of this dissertation, this reservation is one which may have gravity regarding any managerial implications presented in this body of work.

Whether or not the post-structuralist criticism is seen as effective in this regard, it is nonetheless conceivable along the same tangent that critical realism may be overreaching in its attempt to discern agency from an objective social structure, considering its underlying ontological commitment (Wheatley, 2019; Willmott, 2005). In critical realism, agency and social structure are perceived to be independent yet still somehow interconnected; Agency is seen as nested in social structures, giving it emergent causal properties—yet at the same time, social structures are also considered susceptible to transformation by agency (Bhaskar, 1989; Elder-Vass, 2010). Due to the commitment to stratified ontological underpinnings, maintaining this distinction may cause critical realism to put an excessive emphasis on intangible rules and regularities (Sorrell, 2018).

The notion that social structures comprise open systems is a core feature of the critical realist social ontology. In other words, constant conjunctions of events comprising consistent regularities are not expected to be present in social structures in the same way as in closed systems (Buch-Hansen, 2002). However, the mere recognition of agency and the open state of the system do not automatically discount the possibility of observable regularity from surfacing (Potter, 2003). As long as this limitation regarding the interplay of agency, social structure, and regularity is acknowledged, the critical realist approach can be deemed well-suited for providing a multi-level perspective on emerging socio-technological systems. In this dissertation, the limitation is addressed by specifically examining the interlink between agency and social structure through the perspective of power structures and governance, as delineated above in Section 3.1.2.

In conclusion, critical realism as a methodological approach in this dissertation is a careful balancing act—push it too far in the direction of the positivist dogma, and the ability to adequately describe open social systems is lost in the rigidity. On the other hand, a step too far in the interpretivist domain, and any capability for descriptions of causality and actionable normative content escapes. In this dissertation, however, the balancing act is justified, as it arguably provides the best of both worlds.

3.2.2 Critical evaluation of units of analysis and observation

One potential weakness of this dissertation is that due to the qualitative nature of the included articles, some of the general findings may have been affected by a comparative baseline subject to an ecological fallacy. In the academic and business literature on multi-sided platforms, platforms of this kind are portrayed to quintessentially exhibit certain kinds of structure, operative logics, and behaviour, stemming from certain kinds of motivations and ambitions. Generalizations are made about the efforts of platforms to lower the barriers of entry into the market via the platform, to foster network effects in order to generate a lock-in effect of increased switching costs, to utilize certain kinds of asymmetric pricing structures platform services, and so on (see *e.g.* Boudreau, 2010; Hagiu, 2014; Parker & Van Alstyne, 2014). While unquestionably typical of multi-sided platforms, such motivations and operative logics cannot necessarily be assigned to individual platform cases simply on the basis of general characterizations.

Respectively, another potential weak point in this body of work is that, to some degree, the findings may suffer from an exception fallacy. Due to the chosen research design, the conducted analyses are mainly based on only a handful of existing and simulated blockchain systems. Thus, inferring differences between the general characteristics of conventional multi-sided platforms and blockchain systems constituting multi-sided platforms may be subject to excessive reductionism in this regard. Of course, critical realism as a methodological approach does not aim to produce generalizable conclusions in the same way as the constructivist viewpoint, for example. Nonetheless, a degree of prudence must be maintained in this regard when interpreting the results of this dissertation.

On a more generic level of critical evaluation, one could argue that the analyses in this dissertation suffer from a lack of parsimony to some degree due to the bi-layered perception of the unit of analysis as well as five different perspectives, each with varying units of observation associated with them. However, this concession has been a conscious and acknowledged choice in an effort to avoid some of the methodological pitfalls of critical realism. The bi-layered approach to the unit of analysis was adopted to ensure that the study does not overstep its mark in trying to distinguish agency from social structure. Respectively, the five perspectives were incorporated in the research design to ensure that the critical realist approach in this dissertation does not neglect the comparison of the different hypothesized explanatory frameworks.

3.2.3 Critical evaluation of methods and data

In its core, critical realism holds no preference towards any particular set of research methods. However, the critical realist approach recognizes that social phenomena are inherently different from material phenomena (Bhaskar, 1975). As the resulting premise is that different types of knowledge with differing ontological and epistemological characteristics may exist, the use of methodological pluralism and mixed methods is encouraged in critical realism (Mingers *et al.*, 2013; Sorrell, 2018).

While the research process for this dissertation involved a fair degree of methodological versatility, it could be criticised for its excessive reliance on single, conceptual case studies and its scarce use of comparative data and methods. However, as real-world manifestations of the research phenomenon were rare, especially in the early stages of the research process, this limitation was in some respects unavoidable.

Respectively, one could argue that methodological pluralism simply for the sake of form and academic hegemony does not automatically make for more rigorous research. In the study of emerging multifaceted techno-social phenomena, such as blockchain systems, however, a qualitative abductive approach of examining the deeper structures from various perspectives with a multitude of methods is arguably more enlightening than strictly positivist deduction or a purely constructivist inductive focus.

During the later stages of the research process, design science and simulations were also utilized to examine the resource consumption patterns in blockchain systems, and how they need to be taken into account in application development. The use of simulations was the obvious methodical choice for this purpose, as the examined blockchain platform contained an integrated feature for providing the required simulated estimates for resource consumption. Furthermore, testing the resource consumption in a real-world context would have been prohibitively expensive, yet it would have provided no additional insight in comparison to these simulations.

Unlike in article #5, the design science approach utilized in the included article #2 did not commit itself to the guidelines of Hevner & Chatterjee (2010), nor the principles, practices, and procedures of Peffers, Tuunanen, Rothenberger, & Chatterjee (2008) on design science as the *creation and evaluation of innovative IT design artifacts*. Instead, article #2 subscribed to the broader notion of design science as *exploration through design* (Holmström *et al.*, 2009). As a consequence, the research approach in article #2 could be criticised for its weaker scientific rigor in comparison to the more systematically delineated approaches of Peffers *et al.* (2008) and Hevner & Chatterjee (2010).

However, this broader interpretation of the design science approach was necessitated in article #2 by the early stage of technological maturity in inter-industrial system-of-systems-level blockchain implementations. Due to the lack of real-world applications in this domain, developing and evaluating an IT artifact aimed at addressing a pragmatic real-world problem in the application domain would have been highly problematic. Thus, the "gambit" of sacrificing the more rigorous design principles to enable more explorative insight was deemed a beneficial trade-off, considering the larger-scale retroductive research goals of the dissertation. Nonetheless, to reinforce the robustness of the study, two rounds of expert interviews were incorporated in article #2 to map how the interviewee perspectives and concerns related to their views and evaluation of the design proposal, specifically due to the concerns of weaker scientific rigor of the chosen design science approach.

3.2.4 Critical evaluation of triangulation

Contrary to how the term 'triangulation' is most often used in organizational science, it is noteworthy that more often than not, the practice seems to produce divergent results rather than convergent ones. So too is the case with this dissertation. The benefit of such divergent triangulation, however, is that it can provide an understanding on the fact that there is more to the research problem than any single perspective lets on. However, when different triangulated viewpoints fail to converge, the critical question can also be asked whether the problem domain has been mapped correctly in a valid and reliable way in the first place (Bechara & Van de Ven, 2011).

As stated earlier in Section 3.2.1, by a conscious research design choice, the frameworks utilized in the included articles do not fully overlap with one another in this dissertation. It seems that the tendency in academia is to perceive triangulation as the exploration of a problem domain through narrow, neatly segmented areas of investigation. However, it has been argued that this mentality is prone to overlooking the inter-dependencies between those segments—that is, in a critical realist vernacular, the real structure from which the actual within the observed segments emerges (Buchanan, 2003; Mathison, 1988).

This dissertation engages in triangulation with a more arbitration-oriented mindset, recognizing that in order to understand complex multi-dimensional socio-technological systems, such as blockchain platforms, understanding the dependencies and interactions between all the different triangulated viewpoints is at least as important as the provided viewpoints themselves. Consequently, divergent triangulation is construed as a way to expose those dependencies and interactions—to visualize the lines connecting the dots, so to speak.

4 Contributions

4.1 Key findings in the included articles

Article #1 investigated how the increase of intelligence in goods influences the sustainability of industrial closed-loop ecosystems. During the research process, the study delineated three archetypes of closed-loop systems—inner circles, decentralized systems, and open systems. By examining how these archetypes leverage information resources for collaboration, the study concluded that in order for closed-loop business models to be sustainable, they need to be self-reinforcing. In other words, "virtuous cycles" need to be generated within the business model. By delineating how smart contracts could be utilized to create self-reinforcing business models and new kinds of platform integration, the paper found blockchain technology and smart contracts to be important infrastructural elements for collaboration and value creation in closed-loop ecosystems.

Along the same tangent, article #2 extended on this avenue by investigating whether an inter-industrial product-centric information system could be established as a blockchain platform. Via an exploratory design-based approach, the paper explored the potential for self-reinforcing mechanisms in blockchain platforms, and probed some of the problem domain of applying such mechanisms in practical industrial applications. The study found that while significant challenges currently exist for their implementation, the applicability of blockchain systems has been perceived narrowly in academia, overlooking their potential for facilitating virtuous cycles through self-reinforcing mechanisms. To address this issue, the study lays the foundation for a new design approach where design priority is placed on facilitating these self-reinforcing mechanisms to instigate platform collaboration towards closed-loop ecosystems.

Article #3 made an effort to delineate blockchain systems as platforms from the perspective of platform governance. Identifying blockchain systems as distributed multi-sided platforms, the study set out to delineate the multi-sided markets in which blockchain platforms operate, and to explore how the governance of boundary resources and strategic platform goals was orchestrated between the participating market sides. As a finding, the study concluded that in blockchain platforms the platform provision has been distributed across several market sides. Furthermore, the study found that the native crypto-tokens of the system play a key role in facilitating the incentivization mechanisms for self-reinforcing business models in blockchain platforms.

Whereas article #3 investigated the governance structures between the platform market sides, article #4, in turn, focused on exploring the interaction dynamics between individual blockchain platform participants. By employing a legal doctrinal approach, the study investigated whether blockchain-based smart contracts could constitute legal contracts, and if so, the study made an effort to delineate the boundary conditions for establishing such contracts. As its finding, the study concluded that smart contracts can constitute legal acts. In the process, the study also found that differing from more conventional legal contracts, smart contracts can be utilized to facilitate new types of self-reinforcing mechanisms through open incentivization, enabling new modalities of co-opetition and value co-creation in multi-sided platforms.

Assuming a more operational perspective, article #5 set out to shed light on the question of resource efficiency in blockchain platforms. By making an effort to improve the efficiency of a drafted smart contract application, the study established universal optimization principles for smart contract development. Drawing attention to the meticulous resource optimization requirements in smart contracts, the study also pointed out a need for a new design mentality with an emphasis on system efficiency in blockchain-based applications. As a further finding, the study illustrated why the cost structure of blockchain systems is so problematic for use in conventional business processes and platform applications.

4.2 Synthesis of findings

As its primary objective, this dissertation set out to describe, to delineate, and to understand the phenomenon of blockchain networks as techno-socio-economic systems. In order to shed light on the matter, the dissertation aimed to provide answers for three main research problems: how should blockchain systems be delineated, how are they different from earlier equivalent systems, and what is their transformative impact.

Early on in the research process, it became evident that the theory of multi-sided platforms developed by industrial economists offered a clear, consistent, and versatile framework for delineating blockchain systems. This particular viewpoint also appeared to be surprisingly faintly acknowledged in the realm of academia as well as the business domain. Whatever platform characterizations had been presented for blockchain systems mostly appeared to be rudimentary and vague, either in their delineation of blockchain systems, or in their commitment to any particular stream of platform research.

In delineating blockchain systems, one of the key aspects of the multi-sided platform perspective was that it placed network effects at the heart of the issue as the defining key feature of the entire system. This, in turn, unlocked a more thorough understanding on the dynamics of blockchain networks and their growth. A bigger picture manifested where blockchain systems strive to instigate growth through a positive feedback loop woven into the algorithmic fabric of the system's design.

Applying the supporting perspective of transaction cost economics further elucidated how in this feedback loop crypto-tokens appear to play a pivotal role. Due to the assumptions of opportunism and bounded rationality of the participants, crypto-tokens act as an important binding force holding the platform together by aligning the individual opportunistic goals towards collaboration. Thus, the combined perspective of multi-sided platforms and transaction cost economics led to the notion that the importance of crypto-tokens in the design of blockchain systems has not been fully appreciated in the academic and professional discourses.

Respectively, observing the various modalities and patterns in blockchain systems through the concept of platform boundary resources further elucidated the interaction dynamics and incentivization mechanisms by which these networks emerge and evolve. While the technical and social boundary resources quintessential to multi-sided platforms were identified in blockchain systems, the research process also revealed an entirely new class of internal boundary resources, governing the relationships between all the various platform providers competing within the platform core.

When observed through this lens, it seems evident that deep down at its core, blockchain technology is *a tool for network protocol permeation*. Translated into the language of platform research, it is *an alternative method for deploying and growing multi-sided platforms as ahierarchical peer-to-peer networks*. Contrary to contemporary multi-sided platforms that typically require large initial investments to attract users, the cost of deploying a blockchain platform is very low. This eccentric growth dynamic enables a "fire-and-forget" approach to platform deployment which is not available with contemporary platforms.

While blockchain systems seem to share many common features with more conventional multi-sided platforms, the research process also highlighted a multitude of differences in their characterization. For example, unlike conventional multi-sided platforms, public permissionless blockchain systems seem to constitute nearly perfect switch-role markets. Due to the peer-to-peer nature of blockchain platforms, all the participants are equipotent and equally privileged by default. Therefore, no role or market side is generally off limits to any of the participants, including any of the platform provider service functions constituting the platform's core. Respectively, more vibrant multi-dimensionality of development, stronger inter-platform dynamics, incentivization mechanisms less dependent on contracts, as well as pay-per-use resource allocation are all examples of the features distinguishing typical blockchain systems from how multi-sided platforms have been quintessentially characterized in academic literature.

By delineating blockchain systems as multi-sided platforms, as well as elucidating the differences in comparison to the more conventional platform manifestations, this dissertation also makes an effort to shed light on the transformative impact of blockchain systems—if such an effect exists. Indeed, the research process illustrated that practical applications of blockchain systems are faced with considerable challenges and capacity constraints not found in conventional multi-sided platforms.

Due to the algorithmically equipotent and equally privileged status of all network participants, the quasi-anarchistic governance dynamics of public permissionless blockchain systems can complicate the pursuit of strategic platform goals. Furthermore, as blockchain systems typically require exhaustive database replication, as well as constant inputs of computational work for multi-version concurrency control, their freely exploitable computational resources tend to be subject to extreme scarcity. These capacity constraints are prohibitive of leveraging many of the more conventional platform business models in blockchain systems (see *e.g.* Hagiu, 2014). While the cost of deploying a blockchain platform is low, the operating costs are significantly higher than in conventional platforms. Thus, the new types of scarcity of the system's core resources require entirely new modes of thinking in the design of blockchain platforms and their applications.

However, despite these complications, blockchain platforms do not appear to be completely void of a transformative impact. The synthesis of the findings in this dissertation suggests that blockchain platforms can enable new modalities of co-opetitive process automation, albeit with completely different kinds of structures of cost, governance, and incentivization than what are found in more conventional multi-sided platforms. By enabling far greater configurability of platform boundary resources and applications, blockchain platforms can facilitate spontaneous transactions in a way which extends the possibilities of process automation further outside the company firewall than before. In a sense, it could be said that this possibility of external process automation extends the boundaries of the firm in a way more conventional multi-sided platforms are unable to facilitate. This capability could, for example, provide useful in creating self-reinforcing business models and new kinds of platform integration, rendering it an important infrastructural element for collaboration and value creation in closed-loop ecosystems. The capability could also better enable the deployment of platforms the main service offerings of which are not core to the business processes of any of the participants involved.

4.3 Research questions and primary findings

4.3.1 Research question 1: Characterization

The first research problem in this dissertation was expressed by the following question:

"How should blockchain systems be characterized in relation to the theory of multi-sided platforms?"

In response to the first research question presented above, this dissertation produced one primary finding. This finding is summed up below:

- Primary finding 1 (platform characteristics): *Blockchain systems can be coherently described as multi-sided platforms.*

Primary finding 1 is mainly associated with the main theme of ontological characterization. It comprised inputs mainly from research articles #2, #3, and #4 (see Table 2). To summarize the key inputs, article #2 showed that like multi-sided platforms, blockchain systems depend on indirect network effects for growth and critical mass. Article #3 found that blockchain systems operate in multi-sided markets, exhibit technical and social boundary resources, and foster complementarities through joint revenue schemes. Article #4 established how smart contracts can constitute platform boundary resources in blockchain systems.

Table 2. The contributing articles for research question 1.

		ONTOLOGICAL CHARACTERIZATION
#	Article reference	Primary finding 1
#1	Rajala et al., 2018	
#2	Mattila et al., 2021	✓
#3	Mattila-Seppälä, 2018	✓
#4	Lauslahti et al., 2018	✓
#5	Hukkinen et al., 2019	

4.3.2 Research question 2: Differentiation

The second research problem presented in this dissertation was formulated as follows:

"How are the mechanisms in blockchain systems different from the earlier manifestations of their characterized ontology?"

In response to the second research question, the differences in mechanisms were analysed in four dimensions: network dynamics, value creation, coordination mechanisms, and resource allocation. These respective findings can be summarised in the following manner:

- Primary finding 2 (network dynamics): *Blockchain platforms represent a shift away from platform cohesion towards open network dynamics.*

- Primary finding 3 (value creation): *Blockchain platforms represent a transition from a service-structured view towards a more all-encompassing platform co-opetition and value co-creation perspective.*

- Primary finding 4 (coordination mechanisms): *Blockchain platforms extend the transition from contractual obligation towards open incentivization.*

- Primary finding 5 (resource allocation): *Blockchain platforms represent an anomaly in the paradigm of IT resource abundance due to the scarcity of exploitable platform resources.*

These primary findings and their respective theoretical implications are each associated with one of four main themes: 1) network dynamics, 2) service provision, 3) coordination mechanisms, and 4) platform resourcing (see Table 3).

The implications in the theme of *network dynamics* describe how the platform ecosystem and its network of entities changes over time and what kinds of forces and mechanisms influence those changes. This theme is touched upon by primary finding 2 and it mainly contains inputs from research articles #1, #2 and #3. In detail, article #1 described blockchain systems as potential tools for self-reinforcing business models and new dynamics for platform integration. Article #2, in turn, demonstrated that blockchain systems can enable resilient process automation in highly dynamic multi-operator environments. Article #3 found that blockchain platforms can constitute highly dynamic switch role markets.

The theme of *value creation* covers implications which have to do with how services are provided in blockchain platforms: what does the business models landscape look like for platform providers and complementary service providers, how is value created by the network, who captures the value in the value chain, and so on. This theme bases its implications on research articles #1, #3, and #4. To elaborate, article #1 depicted smart contracts as potential key elements in establishing closed-loop value chains. Article #3 delineated how the incentives of the various participants in the system can be aligned through crypto-token-based revenue schemes. Article #4

Table 3. The contributing articles for research question 2.

		NETWORK DYNAMICS	VALUE CREATION	COORDINATION MECHANISMS	RESOURCE ALLOCATION
#	Article reference	Primary finding 2	Primary finding 3	Primary finding 4	Primary finding 5
#1	Rajala et al., 2018	✓	✓		
#2	Mattila et al., 2021	✓		✓	✓
#3	Mattila-Seppälä, 2018	✓	✓	✓	
#4	Lauslahti et al., 2018		✓	✓	✓
#5	Hukkinen et al., 2019				✓

demonstrated how smart contracts can be utilized to enable new modalities of open platform collaboration between competitors.

The theme of *coordination mechanisms* comprises implications describing how blockchain platforms coordinate collaboration between the different platform providers, as well as between the platform core and its complementary constituents. The implications presented in this theme are mainly based on the findings of research articles #2, #3, and #4. In this regard, article #2 illustrated how blockchain systems can incentivize collaboration without the need for explicit *ad hoc* contractual obligations between parties. Article #3 described how the crypto-token-based monetization mechanism can facilitate those incentives. Respectively, article #4 demonstrated that smart contracts can enable parties to co-operate in a mutually beneficial manner without the need for a contractual relationship.

Finally, the theme of *resource allocation* contains implications associated with questions such as how the required platform capabilities are produced, how the platform makes use of its capabilities, and how those capabilities are allocated between different producers and consumers. The implications falling under this thematic category mainly stem from the insights in research articles #2, #4, and #5. Here, article #2 described how the cost of deployment is lower for blockchain systems in comparison to contemporary platforms. Article #4 found that the outcome of efficiency can highly depend on the design of a smart contract and how it is drafted. Article #5 demonstrated that that the low cost of deployment in blockchain systems has the trade-off of high operating costs and platform resource scarcity.

4.3.3 Research question 3: Transformative impact

The third research problem put forward by this dissertation asked the following question:

"What is the transformative impact of blockchain systems on the platform economy?"

Unlike the implications produced by primary findings towards research questions 1 and 2, the implications arising from the answer to the third research question are more practical in nature. These implications can be synthesized as follows:

- Primary finding 6: *The make-or-buy dynamics in blockchain platforms oscillate independently from contemporary multi-sided platforms.*

This primary finding and its respective practical implications are associated with the main theme of development dynamics (see Table 4). The finding synthesized inputs from all of the included articles. To summarize these inputs, article #1 pointed out

Table 4. The contributing articles for research question 3.

		DEVELOPMENT DYNAMICS
#	Article reference	Primary finding 7
#1	Rajala et al., 2018	✓
#2	Mattila et al., 2021	✓
#3	Mattila-Seppälä, 2018	✓
#4	Lauslahti et al., 2018	✓
#5	Hukkinen et al., 2019	✓

that establishing intelligent closed-loop ecosystems requires higher degrees of platform openness. Article #2 illustrated the difficulty of establishing real-world business use cases on top of a fully decentralized blockchain system, highlighting the pressure towards higher degrees of vertical integration in development. Article #3 concluded that the governance of strategic platform goals is challenging in blockchain platforms, thereby also implying pressure towards vertical integration. Article #4 described how smart contracts can redefine the boundaries of the firm and enable higher degrees of horizontal modularity. Article #5 underscored the scarcity of blockchain platform resources and the need for core resource optimization.

4.4 Theoretical implications

4.4.1 Platform characteristics

Primary finding 1: Blockchain systems can be coherently described as multi-sided platforms.

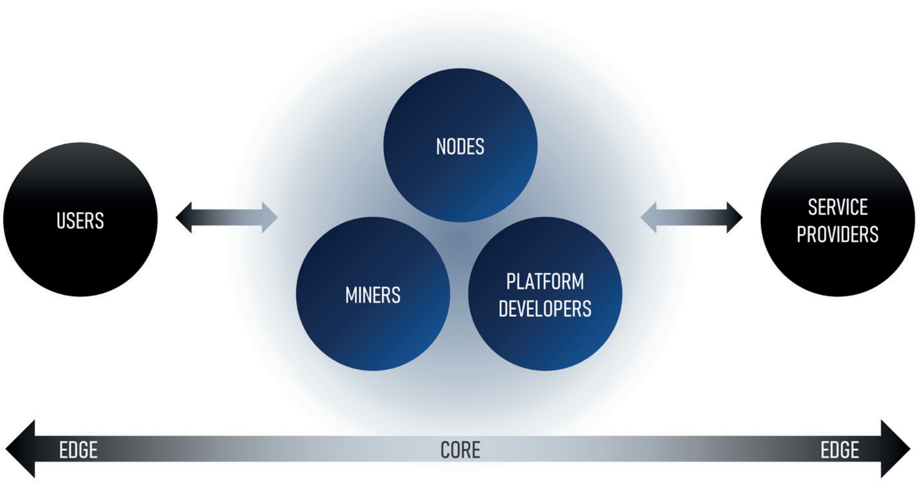
Static and dynamic elements. On the basis of this dissertation, it seems evident that blockchain systems constitute multi-sided platforms in every regard, as defined in the platform research literature. It appears that blockchain platforms share the same platform mentality of combining static elements of an operation to dynamic ones, just like contemporary multi-sided platforms—only through slightly different mechanisms.

In many ways, blockchain platforms comprise much more dynamic systems than contemporary multi-sided platforms. As discussed earlier, blockchain platforms are based on a distributed peer-to-peer network architecture. Therefore, they do not have a specific platform owner monopolizing the provision of the platform infrastructure.

Instead, in the distributed design of the system, all of the platform provision service functions have been scattered across different market sides. Platform provision functions are procured from whichever parties are able to complete a given task to the highest satisfaction of the network participants. In the case of commoditized platform provision functions, such as mining, the decisive factor is the ability to produce the service at the lowest cost possible, in accordance with free market mechanics. In the case of more refined functions, such as core development, however, the decision-making is based on a more subjective evaluation of quality by each participant.

Nonetheless, a platform core element can be delineated in the structure of blockchain platforms (see Figure 2). Much more so than in contemporary multi-sided platforms, however, this blockchain platform core exhibits—in the lack of a better expression—a "fractal-like" ontology. Like the nucleus of an atom, the blockchain core only appears static and coherent to a distant enough observer. Reeling in for a closer perspective, however, the tumultuous nature of the structure is revealed, and the contours are lost in the chaos, much like in an impressionist painting.

Figure 2. The "atomic model of blockchain", describing the platform core (blue) and the complementary elements at the edges (black) in blockchain platforms in terms of market side interactions.

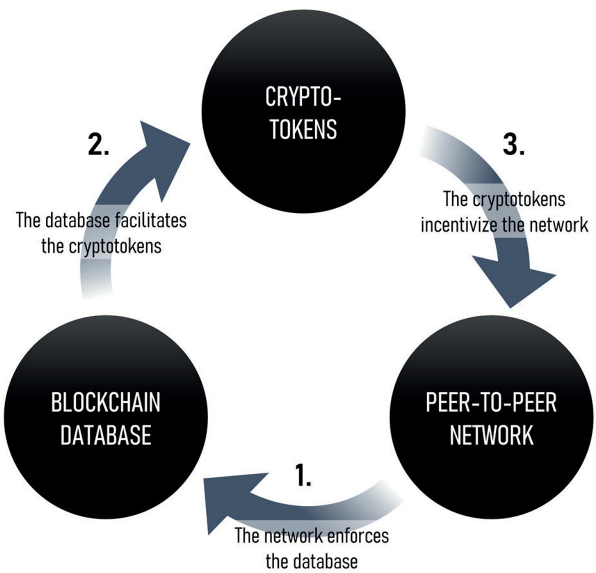


Multi-sided markets. It seems that typically the blockchain platform core manifests out of the collaboration of three platform market sides: the nodes, the miners, and the platform core developers. In this arrangement, the nodes are responsible for maintaining the network's database and validating its authenticity. The miners, in turn, are responsible for maintaining the multi-version concurrency of the network and its database. Lastly, the platform developers are responsible for producing software update proposals , as well as suggestions for fine-tuning and developing the protocol which determines the codes of conduct and the incentives for the platform participants. The complementors in blockchain systems are represented by all the other participating market sides.

Platform governance in blockchain platforms takes place via an elaborate network of interwoven control mechanisms and power relations between the market sides. Like in any other multi-sided platform, the collaboration between the various market sides is governed by a set of boundary resources in blockchain platforms. Most of these boundary resources are facilitated by incorporating them into the network protocol. This protocol governs how the various constituents of the network are to behave and to communicate if they wish to be recognized as a part of the network by its other members.

Network effects. Like contemporary multi-sided platforms in general, blockchain platforms also live and die by their indirect network effects. In fact, even more so than contemporary multi-sided platforms, blockchain platforms are structured in such a way that without sufficient network effects, the security of the network database and its single state are compromised. Furthermore, the database and its single state are utilized to create and track the crypto-tokens required for the incentivization of participant collaboration. Therefore, without sufficient network effects, the provision of the platform core itself becomes unfeasible (see Figure 3).

Figure 3. The positive feedback-loop of indirect network effects in blockchain platforms.



Boundary resources. Blockchain systems also clearly employ boundary resources to coordinate collaboration. Technical boundary resources, such as application programming interfaces (*'APIs'*) and software development toolkits (*'SDKs'*) can be clearly observed in the systems (*cf.* Glaser *et al.*, 2018). Respectively, as for social boundary resources, features such as joint revenue models, *e.g.* algorithmically governed mining rewards, as well as developer documentations also appear to be present in blockchain platforms.

As the blockchain platform provision functions have been scattered across multiple different market sides, new relationships of interaction are present which do not normally manifest in contemporary multi-sided platforms. Namely, the interactions between one platform provider and another need to be somehow governed and enforced. In order to establish this collaborative framework, blockchain platforms utilize procedures embedded deep in the very foundations of the platform's most basic fabric, the network protocol. As the network protocol stipulates how the network participants are to connect and communicate with one another, any failure to abide by the protocol will lead to excommunication by the other members of the network, providing a simple yet effective method of enforcement. As a result, the collaboration between the providing entities is held together by an intricate web of algorithmically defined codes of conduct, positive and negative financial incentives and interlocking mechanisms of platform control.

Earlier in this dissertation in Section 2.2, boundary resources were characterized as the operational guidelines and technical tools and interfaces governing the interactions between the platform provider and the platform participants. To elaborate this definition, in the research literature on multi-sided platforms boundary resources have also been described as the tools employed to stabilize particular relationships between multiple actors operating in different social realms (Ghazawneh, 2012). Building on these characterizations, the blockchain network protocol, the incentive structures embedded within it, and the control mechanisms in blockchain systems can be perceived as a group of boundary resources. However, aimed at governing the "intra-platform" relationships between all the platform providers in various market sides, they appear to constitute a completely new class of boundary resources in multi-sided platforms.

- *Supporting finding 1: Blockchain systems exhibit an entirely new class of internal boundary resources which are employed to govern provider-to-provider relations.*

4.4.2 Network dynamics

Primary finding 2: Blockchain platforms represent a shift away from platform cohesion towards open network dynamics.

Switch role markets. Quintessentially, the collaboration in contemporary multi-sided platforms tends to be more loosely organized in comparison to the traditional company paradigm. Contemporary multi-sided platforms typically externalize some of the development of product and service innovations and leave it up to the markets to determine which ones are the most satisfactory in complementing the platform. Instead of meticulously coordinating production processes, the platform provider carefully coordinates the boundary resources and fine-tune the balance between the subsidies and fees imposed on their constituent market sides in order to attract participants and to foster indirect network effects between them (Hagiu, 2014; van Alstyne *et al.*, 2016).

Yet, on a higher level of abstraction, there is a strong sense of cohesion still present in these systems. For example, while the platform's design may considerably develop over time, the control structure is seldom, if ever, completely overhauled. The platform entity which controls the elements, and acts as the hub under which all the auxiliary constituents are always subjugated, remains largely unaltered. To put it in terms of platform vernacular, contemporary multi-sided platforms can be characterized by a higher degree of switch role market mechanics than what is usually seen in traditional companies (Aspers, 2007).

However, even in contemporary multi-sided platforms, the static core of the platform—what could be called "the market for platform provision"—is typically not open to the edges for participation. In other words, in contemporary multi-sided platforms, the platform owner reserves the right to offer platform provision services to the platform participants. While complementing participants are welcome to partake in the platform ecosystem in many different market sides (*e.g.* application user & application developer), the market relationship between the platform owner and the auxiliary constituents always remains a fixed-role market.

As blockchain platforms are based on an open-access peer-to-peer network, no party can be excluded from participating in any of the system's market sides—including the ones involved in the provision of the platform's core architecture. Instead of monopolizing the platform provision, the required functions are procured from whichever parties are able to complete a given task to the highest satisfaction of the network participants. In the case of commoditized platform provision functions, such as mining, the decisive factor seems to be the ability to produce the service at the lowest cost and with the shortest production time, in accordance with free market mechanics. In the case of more refined functions, such as platform development, however, the market preference appears to be based on a more subjective evaluation of quality by the network participants.

- *Supporting finding 2a: Unlike contemporary multi-sided platforms, blockchain systems constitute more elaborate switch-role markets. The provision of the entire platform infrastructure is externalized and procured according to free market mechanics.*

Multi-dimensional development. In addition to the fixed-role market structure between the provider and the participants, the platform cohesion in contemporary multi-sided platforms is also manifested in the one-dimensionality of the platform evolution. Even if the platform and its ecosystem dynamically evolve over time—perhaps even developing new platforms inside or on top of the ecosystem—the multi-sided platform typically does not metastasize independent platform fragments or spinoff variants without the explicit consent of the platform authority.

Herein lies another difference between blockchain platforms and contemporary multi-sided platforms. Built on open-source principles, blockchain platforms strongly reflect the idea that anyone should be able to take the source code of the system, modify it in whatever way they want, and publish their own derivative version alongside the original—a principle often referred to as 'the right to fork code' (De Filippi & Loveluck, 2016; Nyman & Lindman, 2013). Due to this open-source principle, the practice of forking—that is, editing the source code of the system and deploying a modified installation—is a common natural occurrence in the evolution of blockchain platforms (Glaser *et al.*, 2018).

Through this culture of forking, the coordination of boundary resources and the balancing of market-side incentives are entirely externalized in blockchain platforms. In practice, blockchain platforms take the multi-sided platform mentality of externalizing complementary innovations and testing their success directly in the market—and apply it to the platform core. If any individual or group feels that the incentivization structure of the network is unfair, non-optimal, or otherwise somehow in need of improvement, they can take the source code of the system, fine-tune it, and deploy a competing version of the network with modified protocol rules. The platform participants would then be faced with the choice of either sticking to the old network or migrating to the new environment. The adoption rate of the two competing platform instances would determine whether the new proposal was accepted or rejected. Alternatively, in the case of an irreconcilable split decision, the platform might also permanently skew in half to form two new smaller platforms, each with its own devout group of supporters.

In other words, the fine-tuning of the market-side incentives in blockchain platforms takes place via an evolutionary process steered by market adoption and the presence of indirect network effects. Each market side has an inherent incentive to drive their own interest in the development of the platform's incentive structure. However, each market side also has a vested interest in ensuring that the platform does not disintegrate into smaller fragments, as this would decrease everyone's utility due to the loss of mutual network effects. Through these driving forces, the market zeroes in towards more fine-tuned and more balanced versions of the platform. As forked versions with an incentivization structure too favouring of a particular market side disintegrate, the users migrate towards the most balanced compromises capable of producing the strongest indirect network effects (see Glaser *et al.*, 2019). Thus, blockchain platforms evolve very differently from contemporary multi-sided platforms, in a much more multi-dimensional and less cohesive manner.

- *Supporting finding 2b: Contemporary multi-sided platforms externalize innovation development but internalize the balancing of market-side incentives to maximize the growth of the platform ecosystem. Blockchain platforms externalize both of these aspects.*

Once again, however, in order to fully distinguish the platform-like features in blockchain systems, one must take a step back and look at the issue through the perspective of the blockchain platform domain as a collective. In fact, for this described mechanism of blockchain platform development through forking, one could indeed justifiably ask the question of whether the pre-forked and post-forked versions of the blockchain network actually even constitute the same platform. While the answer is somewhat a matter of perspective, since blockchain platforms do not have an identifiable owner or a single provider, whether or not a forked platform is the same entity as before is largely irrelevant. However, it seems that amongst the general public, the perception of platform identity tends to follow the majority user adoption, giving further credence to the notion that the essence of a blockchain platform is ingrained in its network effects.

Inter-platform dynamics. The platform identity conundrum discussed above serves as an illustration of the larger point that blockchain platforms tend to exhibit more vibrant inter-platform development dynamics than contemporary multi-sided platforms. For example, some blockchain platforms, *e.g.* Litecoin, have carved out a market niche for themselves as the testbeds for larger and more prominent blockchain platforms. With their help, risky protocol updates and system modifications can be tested and adopted without risking the performance of the larger installations. Similarly, if a technical breakthrough is made in one blockchain platform's design, its benefits are easily adopted by the entire industry. As no one can be prevented from building and innovating on top of the existing blockchain platform designs, no entity has the power to prevent or to slow down the evolution of blockchain platforms—all they can try to do is to outperform the competing visions for the direction of the future development and to win over sufficient network effects for their design to perpetuate.

Another point illustrative of the differences in inter-platform dynamics between contemporary multi-sided platforms and blockchain platforms is their respective takes on platform interoperability in general. In the realm contemporary of multi-sided platforms, it is not entirely uncommon for platform providers to limit interoperability and data portability through so-called 'walled gardens'. By increasing switching costs, platform providers are able to generate a stronger lock-in effect and to keep users within the platform ecosystem instead switching over to another platform completely. (Gawer, 2014; Hazlett, Teece, & Waverman, 2011; Parker & van Alstyne, 2005) Conversely, as excluding parties from developing the core is not feasible in blockchain platforms, their domain is saturated with endeavours to develop interoperability solutions between individual blockchain platforms.

- *Supporting finding 2c: Blockchain platforms exhibit more vibrant multi-homing dynamics and inter-platform development than contemporary multi-sided platforms.*

4.4.3 Value creation

Primary finding 3: Blockchain platforms represent a transition from a service-structured view towards a more all-encompassing platform co-opetition and value co-creation perspective.

Network deployment. Contemporary platform business models are mainly based on a service-structured view in their monetization. In other words, platform provision is monetized via the connections and service interactions between particular market sides, specifically targeted due to their highest dependency of the platform's network effects (Hagiu, 2014). In blockchain platforms, however, the monetization mechanism for the platform provision reflects a more all-encompassing platform value perspective and an open investment model.

In blockchain platforms, the crypto-tokens utilized for payments within the platform ecosystem have an important role to play as the key monetization vehicle driving the platform's growth and development. Essentially, blockchain-based crypto-tokens seem best described as some sort of an amalgamation of platform equity, platform-specific local currency, and elements of crowdfunding. As the transactions conducted within a blockchain platform ecosystem are typically settled by using a limited supply of these tokens, their exchange value is directly proportional to the amount of economic activity around the platform, and thus by extension, its network effects. Therefore, anyone hoping to profit from the growth of the blockchain platform can buy some of these tokens out of circulation and hold them as an investment. Later on, once the platform has grown, the increase of its network effects can be monetized by selling the tokens back into circulation at a higher exchange rate.

In some loose sense, the principal monetization mechanism in blockchain platforms can be analogized to investing in the growth of economies by acquiring some of their national currency and leveraging its value against another national currency. In principle, the mechanisms and the value propositions between the two are similar, only one takes place at the level of a national economy, and the other is specific to a particular digital multi-sided platform ecosystem.

Through this monetization mechanism, any participant in any market side of a blockchain platform can align their incentives in such a manner that, in principle, any contributions towards the platform's growth can be profited on. Thus, the mechanism also functions as an incentive to design and to deploy entirely new blockchain networks. Through this bottom-up platform business model, blockchain networks can be deployed in an open-source fashion and with significantly lower costs than required by the top-down platform business models of the contemporary multi-sided platforms.

- *Supporting finding 3: Blockchain systems enable new bottom-up platform business models and new mechanisms to monetize platform growth, available to all market sides.*

Core development. The crypto-tokens also function as a monetization vehicle for core development in established blockchain platforms. As the network forks into separate factions, so too does the record of crypto-token transaction history, effectively forming two different units of tokens with the same history of origins. Effectively, anyone in possession of tokens at the moment of the forking will have that original balance carried over to both resulting ledgers in both offshoots of the network.

Evidently, a balance of tokens in a blockchain network void of users is worthless. Therefore, participants finding themselves in the middle of a forking situation have an incentive to sell their balance of tokens in the branch the success of which they do not have high hopes for. As the participants are rearranging themselves into their preferred factions, the market turbulence provides an opportunity for anyone believing in the triumph of a given fork to support its growth and to profit from its success. At the same time, the exchange rates of the tokens in different forked branches also act as price signals, providing the participants with information on the popularity of various version proposals. Thus, the coordination game may also exhibit features of a Keynesian beauty contest, making the evolution of forking somewhat less chaotic and more coherent (see Conley, 2017).

Complementary assets. In some respects, the provision of complementary products and services also reflects a more all-encompassing platform value perspective in blockchain platforms. The same monetization mechanism discussed above is also available to the complementing market sides. Furthermore, some proposals for interesting applications have been put forward which also reflect the platform value perspective in another form. To illustrate, the concept of crypto-mining payments is an example of a blockchain platform innovation where value creation is approached in a very unique manner. By making use of the mining process and its respective platform incentivization mechanism, parties can carry out transactions by disentangling the contributor of the work and the recipient of the payment from one another. In this described arrangement, each payment transaction also simultaneously contributes to the provision of the payment-processing architecture, essentially providing another feedback loop of positive indirect network effects.

4.4.4 Coordination mechanisms

Primary finding 4: Blockchain networks extend the transition from contractual obligation towards open incentivization.

Absence of contracts. According to transaction cost economics, one of the basic answers to the question of why there are companies in a specialized economy in the first place, is that companies bring down the costs of combining resources from different owners for joint production (Moe, 1984). To extract value, companies optimise production by maintaining a normative structure to the coordination process (van Alstyne *et al.*, 2016). According to the basic premises of economic theory, this coordination requires transference of rights and obligations, traditionally achieved by the use of legal contracts (Cheung, 1970).

By deviating from this traditional company paradigm, multi-sided platforms assume a different approach to extracting value. Rather than meticulously coordinating production processes, their main attention is on the effective facilitation of interactions between different actors representing various market sides. By lowering the barriers of entry into the market, platforms focus on persuading participants to join up and to collaborate, thereby instigating growth and fostering stronger network effects. In this mode of operation, efforts of governance mainly take place at the level of the entire platform ecosystem (van Alstyne *et al.*, 2016). While legal contracts still remain an important part of the platform governance toolkit, legal arrangements are perceived more as enablers, rather than constrictors. Just as with many other boundary resources in platforms, the main aim is to incentivize, rather than to obligate.

It appears, in other words, that contemporary multi-sided platforms have expanded the traditional company perspective on how collaboration, production, and innovation can be organized in multi-sided markets. Similarly, the advent of blockchain systems seems to have expanded this perspective even further along the same tangent. In comparison to contemporary multi-sided platforms, blockchain systems have an even more direct focus on incentivization instead of obligation—the use of judicial contracts being virtually inexistent.

For example, let us consider one of the most prominent and well-established blockchain systems at the time of writing, the Bitcoin cryptocurrency payment processing network. Measured in hashing power (operations per second), the Bitcoin network is likely the fastest computing grid in the world, by far outperforming the world's fastest TOP500 supercomputers combined[1]. And yet, this behemoth of a network has emerged entirely out of the mere deployment of an open-source network protocol—without the need for any contractual agreements to be signed or any legal rights to be enforced through litigation at any point along the way.

Warping incentives. By algorithmically weaving crypto-token incentive structures into their network protocol, blockchain systems can warp the game-theoretical settings which their participants are faced with when weighing different courses of action within the platform ecosystem. As this warping is executed at the level of the open-source network protocol, it takes place in a transparent and predictable way. Consequently, participants can anticipate and trust one another to behave in a certain manner out of self-interest, and thereby collaboration is enabled, even if they do not trust one another to behave honestly.

Some blockchain platforms, such as Ethereum, offer a Turing-complete language for creating persistent scripts. Despite their misleading name, these so-called 'smart contracts' are in fact another manifestation of this game-theoretical warping in blockchain systems. The smart contracts enable any participant to create a designated workflow of warped incentives, specifically designed for a particular situation or purpose. Effectively, as the execution of these persistent scripts cannot be easily prevented by any unauthorized party in the network, parties can rely on the enforcement of the anticipated workflow, much like with contracts, but without the need to engage in legal arrangements or contractual processes of any kind.

To summarize the relationship on a general level, one could say that the creation of companies introduced a standardized framework for coordinating *production*. Respectively, it could be said that multi-sided platforms presented a standard framework for coordinating *innovation*. Much in the same way, it could be argued that blockchain systems have provided a standard framework for coordinating *incentivization*. Whereas contemporary multi-sided platforms enable a relatively narrow band of incentivized auxiliary innovation activities, blockchain platforms can be perceived more as generic incentivization engines.

Algorithmic fabric. Blockchain platforms replace judicial contracts, such as terms of agreement—traditionally perceived as social boundary resources—with incentive structures manifesting from software and protocols. As the latter are generally categorized as technical boundary resources, it seems that in blockchain platforms, the whole concept of incentivizing participation has shifted into this realm of technical boundary resources. Whereas contemporary platforms define participant incentives through the use of social boundary resources, in blockchain systems, generic incentivization tools are offered in the form of a "software development kit", with detailed documentation and guidance for developers.

It should be noted that certain elements of social trust and off-chain decision-making still exist around blockchain platforms. For example, in Bitcoin, the participants have to trust that the nodes and the miners of the network continue to use the same genesis block as the origin of their canonical blockchain. Usually, however, the mechanisms of coordination which have been formalized in blockchain platforms are technical in nature. Consequently, it seems that not only are technical boundary resources much more common in blockchain platforms than in contemporary multi-sided platforms, but it is also becoming increasingly difficult to differentiate between the two types of boundary resources in these systems.

- *Supporting finding 4: Blockchain platforms make it increasingly difficult to differentiate between technical and social boundary resources.*

4.4.5 Resource allocation

Primary finding 5: Blockchain platforms represent an anomaly in the paradigm of IT resource abundance due to the scarcity of exploitable platform resources.

The cost efficiency of information systems is not something which has been paid a lot of attention in multi-sided platforms the past decades. In fact, ever since the 1980s, information technology systems in general have been largely evaluated by other factors than their resource consumption. It appears, however, that due to various concurrent rising trends in the field of IT (*e.g.* edge computing and streaming services), the efficiency perspective is once again becoming topical for the platform economy.

Blockchain systems employing a proof-of-work consensus mechanism may consume extremely high amounts of energy to maintain their single state—even to a point of sheer wastefulness. However, from the platform participants' perspective, blockchain systems nonetheless strongly reflect a trend towards platform resource frugality. From a computer science perspective, blockchain systems can be characterized as *finite state machines*. Typically, they allow users to employ and to customize computational workflows which can then be executed upon request. However, in order to maintain a single state across the entire system, all the nodes of the network must perform all of the computational workflow tasks autonomously. Effectively, this drastically limits the computational capacity of the network, making the customizable workflow resources of the network extremely scarce.

Due to this scarcity, blockchain systems operate on the basic principle of optimizing their workflow resource expenditure through free market mechanics. In practice, computational resource consumption is priced on a strict pay-per-use basis. Thus, computational resources are allocated to the execution of the workflows which bid the highest fee in the network. As a consequence of this free-market mechanism, the users and complementary service providers alike are left to optimize their own use of the network's computational resources. In practice, meticulous attention needs to be paid to the resource efficiency of any software code and workflow structures designed to be run on the platform. Thus, a completely different mode of thinking towards resource efficiency is required of both users and service providers than in contemporary multi-sided platforms.

- *Supporting finding 5: Contrary to contemporary multi-sided platforms, blockchain systems price their platform resources on a pay-per-use basis. Consequently, platform participants are responsible for the optimization of their use of the platform's system resources.*

4.5 Practical implications

4.5.1 Development dynamics

Primary finding 6: The make-or-buy dynamics in blockchain platforms oscillates independently from contemporary multi-sided platforms.

In the research literature on multi-sided platforms, the dynamics of the platform core and the edge has been described as a double-helix structure. According to this idea, the emphasis on platform resources and capabilities tends to follow a pattern of oscillating back and forth between integrated vertical core-based solutions, and modular horizontal structures leveraging the platform's edge capabilities. As new disruptive innovations emerge in the market, sooner or later some of them may reach critical mass and blow up in popularity, leading to the innovator's market power rapidly growing. As the popularity of the innovation increases, so too does the profitability of incorporating proprietary elements into the mix. Likewise, as the network effects become stronger due to increases in the user base, the switching costs become higher, further strengthening the lock-in effect. As a result, the incentives for the dominant market players to engage in vertical integration increase, and the market shifts towards an emphasis on platform core capabilities and centralized control (Fine, 1996, 2008).

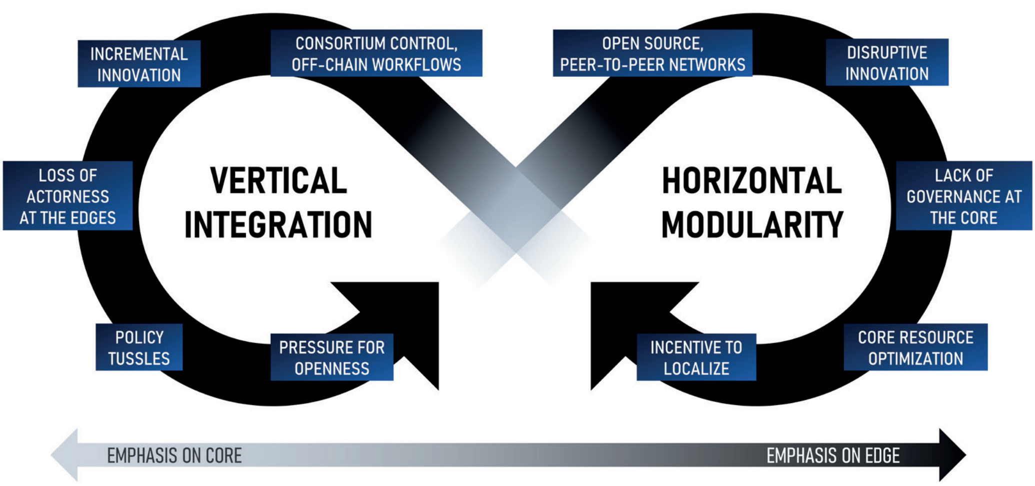
Once the market has sided towards vertical integration, incremental innovation begins to dominate. The lack of modularity may eventually cause frustration and subterfuge at the edges of the platform. Similarly, due to the rigidity of the vertically integrated structure, policy tussles may arise. As a result of these tensions, the pressure grows to increase openness and modularity in the network, and the market switches over to a mindset of horizontal modularity, with open architectures supporting vibrant edge activity. This, in turn, enables a higher rate of disruptive innovation, and the cycle repeats all over (Fine, 1996, 2008).

Building on this idea of Fine's double-helix structure, the dynamics between the core and the edge in blockchain systems can be characterized in a very similar fashion (see Figure 4). As technology platforms, blockchain systems have enabled a new kind of computational cyberspace where completely new social constructs and disruptive social paradigms can be innovated. While no true "killer apps" have so far manifested on top of this technological underlay, some glimpses have been seen of what such potential new social constructs might eventually entail. For example, the initial coin offering boom, the development of decentralized autonomous organizations, as well as the crypto-mining nanopayments give weak signals of potential future applications.

Blockchain systems have sometimes been described as "democratic", "anarchistic", "algorithmically governed" or even "technocratic". In critical view, however, none of these characterizations seem accurate. While an intricate web of control mechanisms typically exists between the various market sides participating in blockchain platforms, in terms of strategic governance, these systems are best described as quasi-anarchistic. In other words, opaque relationships of influence are at play outside of the technological realm of blockchain platforms, yet the system itself is largely incapable of formalized strategic decision-making.

Due to the lack of strategic governance and the scarcity of core infrastructural resources on blockchain platforms, these systems drive their constituents to optimize

Figure 4. The "blockchain double helix", describing the dynamics of the core and the edge in blockchain platform development (adapted from Fine, 1996, 2008).



their resource consumption through a strict system of free-market pricing and monetary incentives. In essence, the fees and incentives are the system's way to signal to its users that a blockchain system is not a substitute for a cloud storage or a supercomputer—but rather what it offers is *Single-State-as-a-Service*.

The lack of formalized governance and the scarcity of utilizable resources on blockchain platforms imply that there is an inherent pressure for participants to minimize their use of the platform's computational resources and to move their data-handling off-chain as much as possible. This creates an incentive to rely more on local resourcing, to *make* rather than to *buy* workflow execution from the blockchain network, and to increase vertical integration in the information technology stacks.

Consequently, the market begins to shift over to an emphasis on vertical integration and centrally controlled proprietary systems. Incremental innovation takes precedence in private blockchain consortiums. The strong focus on consortium-specific solutions and the lack of transparency hinder the development of system-of-systems-level solutions. As a consequence, frustration at the edges of the system grows due to the experienced loss of actorness, and the enterprise-driven consortium approach may begin to suffer from various kinds of policy tussles.

Due to the focal dominance of incremental innovation in privately governed consortia, the loss of actorness at the edges, as well as the policy tussles, the pressure may begin to rise to increase openness in the market. Eventually, the market may shift over back towards open source development, peer-to-peer solutions, and an emphasis on horizontal modularity. As one recent example of this is, one might mention Facebook's Libra initiative which early on involved a commitment to transition into a public permissionless blockchain architecture within five years of its deployment. In April 2020, this commitment was, however, dropped from the initiative's vision (Libra Association, 2020).

Currently, contemporary multi-sided platforms are facing some pressure for increased openness (see *e.g.* Fung & Liao, 2020). Policy tussles, such as antitrust tensions, accusations of political platform censorship, and the lack of transparency in the artificial intelligence algorithmics and in the handling of user data are paving way for a potential shift towards an increase in horizontal modularity. Curiously, however, it appears that while contemporary digital multi-sided platforms appear to be experiencing some pressure to increase openness and horizontal modularity, at the same time, blockchain systems are experiencing pressure for a shift in the opposite direction: increased use of local device intelligence and off-chain workflows, as well as more prominent vertical integration of the information technology stack.

5 Discussion

5.1 Research question 1: Characterization

The findings of this research indicated that public permissionless blockchain systems can be comprehensively and coherently described as multi-sided platforms. In their holotypic form, blockchain systems exhibit all of the key characteristics delineated in the academic multi-sided platform literature. By analysing and delineating the governance relationships of the different participatory factions in a case study of the Bitcoin platform, Mattila & Seppälä (2018) showed how the Bitcoin network operates in multi-sided markets. Lauslahti *et al.* (2018), in turn, used conceptual case studies to show how the programmable logic of Ethereum smart contracts can be used to formulate boundary resources for specific interactions between participants and to support the production of complementary assets. Respectively, by applying design science, Mattila *et al.* (2021) conceptualized how public permissionless blockchain systems can be set up to foster the growth of the network through a positive feedback loop of indirect network effects.

The answer to the first research question is significant in its scientific contribution. So far, blockchain systems have not been delineated within a comprehensive platform framework at the socio-economic-judicial level. In most instances where blockchain platforms have been discussed in relevant contexts, the subscription to a particular platform convention has remained ambiguous—usually by the virtue of such elaborate platform considerations falling outside the focal scope of those studies (see *e.g.* Athey *et al.*, 2016; Böhme *et al.*, 2015; Catalini & Gans, 2016). The systematic delineation of blockchain systems as platforms in this dissertation contributes to the academic discussion by describing in detail how established terminology can be applied to blockchain systems in a meaningful manner. Furthermore, the conceptual development carried out in this dissertation also contributes to academia by introducing new concepts, such as the atomic model of blockchain, and by building on top of pre-existing ones, like in the case of the blockchain double-helix.

Respectively, while the phenomenon has been acknowledged by some authors, blockchain systems have not been discussed at length in the mainstream academic literature on multi-sided platforms (see *e.g.*Parker *et al.*, 2017). While some more comprehensive delineations have been presented, with defined subscriptions to the multi-sided platform research convention (see *e.g.* Conley, 2017; Glaser *et al.*, 2018), the earlier analyses remain somewhat limited in scope and do not systematically account for all of the characteristics of multi-sided platforms, as delineated in the research literature. As such, this dissertation contributes to the academic discourse on both multi-sided platforms as well as blockchain systems by providing a comprehensive delineating framework which can be used for further investigations, in both positivist and interpretivist domains.

As discussed in Section 3.2.2, it should be acknowledged, however, that the answer provided to the first research question is based only on a handful of public permissionless blockchain systems. It cannot be said on the basis of this dissertation whether all manifestations of blockchain technology constitute multi-sided platforms. Indeed, as pointed out earlier in this dissertation, the concept of a 'blockchain' can be a highly elusive one. More importantly, however, in the explanatory spirit of critical realism, the dissertation shows that the multi-sided platform framework can be meaningfully applied to the examination of public permissionless blockchain systems from a wider socio-economic perspective.

5.2 Research question 2: Differentiation

The examination of blockchain systems through the superimposed platform framework illustrated that blockchain platforms can offer an alternative method for the deployment, growth, and sustenance of multi-sided digital platforms. Whereby the initial costs of platform deployment have traditionally been relatively high, the eccentric growth dynamic in blockchain platforms enables low initial investments—but with the trade-off of significantly higher operating costs and platform resource scarcity. In other words, while deploying blockchain platforms can be relatively easy, finding use cases of genuine value can be difficult in conventional platform settings and business applications.

The second primary finding of the dissertation stated that blockchain platforms represent a shift away from platform cohesion towards open network dynamics. This finding was synthesized from several research observations. Through conceptual case studies and secondary interviews, Rajala *et al.* (2018) illustrated how blockchain systems can be utilized to create self-reinforcing business models and new kinds of platform integration dynamics. Mattila *et al.* (2021) employed design science, systematic combining, and a conceptual case study to point out that blockchain systems can maintain process automation workflows intact even in the case of highly dynamic and multi-actor environments. Respectively, by analysing the market side structures and interactions in the Bitcoin cryptocurrency platform via a case study design, Mattila & Seppälä (2018) discussed how in public permissionless blockchain systems, the market side interactions can constitute nearly perfect switch role markets.

As a result of the second primary finding, the dissertation makes a contribution to the discussion regarding platform cohesion in multi-sided platforms (Aspers, 2007; Hagiu, 2014; van Alstyne *et al.*, 2016). By challenging the notion of the platform core as a cohesive structure representing fixed-role markets, the dissertation expands the understanding on how platform core mechanics can be configured as switch-role markets.

The third primary finding concluded that blockchain platforms represent a transition from a service-structured view towards a more all-encompassing platform co-opetition and value co-creation perspective. This key finding was underpinned by several research observations as well. Firstly, through conceptual case studies and secondary interviews, Rajala *et al.* (2018) observed how blockchain-based smart contracts represent an important element in creating closed-loop ecosystems for the circular economy. Through its conceptual case study analysis, Mattila–Seppälä (2018) delineated how the crypto-token-based monetization mechanism in Bitcoin cryptocurrency platform enables any participant to align their incentives with the indirect network effects and the development of the platform ecosystem as a whole. Respectively, Lauslahti *et al.* (2018) demonstrated how blockchain-based smart contracts can be designed to enable new modalities of open engagement and platform collaboration.

In this regard, the dissertation contributes to the academic discussion on platform co-opetition (Cohen & Zhang, 2016; Niculescu *et al.*, 2018; Yoo *et al.*, 2020). By describing how blockchain platforms can enable new modalities of co-creation, this research adds to the understanding of how co-opetition can manifest in multi-sided platforms.

The fourth primary finding synthesized that blockchain platforms extend the transition from contractual obligation towards open incentivization. To construct this synthesis, several research observations were combined. The observation from the case study of Mattila–Seppälä (2018) on the crypto-token-based monetization mechanism in Bitcoin mentioned above played a key role for this synthesis as well. Additionally, Lauslahti *et al.* (2018) showed through conceptual case studies how blockchain-based smart contracts can enable interacting parties to reach their contractual goals without actually needing to enter into a contractual relationship of any kind. Furthermore, in its design proposal, Mattila *et al.* (2021) presented a conceptualization whereby industrial agents could be incentivized to provide product data on product individuals and to operate the product data platform via a blockchain-based design without any need for *ad hoc* contractual obligations.

In earlier platform literature, it has been hypothesized that the coordination problems related to the collaboration around multi-sided platforms cannot be solved through price incentives (Boudreau & Hagiu, 2008). This dissertation also contributes to this discussion by demonstrating that the incentivization mechanisms in blockchain platforms are significantly more all-encompassing than in contemporary platform models. Thus, the implication is that a wider variety of coordination problems and market failures can be addressed through the blockchain platform approach (see also Catalini & Gans, 2016).

The fifth primary finding stated that blockchain platforms reflect an anomaly in the paradigm of IT resource abundance due to the scarcity of exploitable platform resources. Through its design science conceptualization, Mattila *et al.* (2021) pointed out that the initial cost of launching a blockchain system is lower than platform deployment by contemporary means. Respectively, by applying design science to address the problem of cost efficiency in an Ethereum smart contract, Hukkinen *et al.* (2019) showed that this low initial investment of blockchain platform deployment comes with the trade-off of significantly higher operating costs and platform resource scarcity. Lauslahti *et al.* (2018) supported these observations by exploring how blockchain-based smart contracts can be designed in different ways, and how it is up to the creator to draft the smart contract program in a way which guarantees the desired implications.

The efficiency of IT systems has not been at the focus of research attention in recent decades—neither inside nor outside of the multi-sided platform research literature. In this regard, this research also contributes in a broader manner to how digital platforms and IT systems are perceived in academic discussions in the future (see *e.g.* Bharadwaj, 2000; Ives & Learmonth, 1984; Woodward, 1997).

As explained earlier in Section 3.2.1, the critical realist approach in this dissertation mainly engaged in retroductive reasoning. In other words, empirical observations were utilized to create hypotheses on what kinds of mechanisms could account for those observations. Thus, the findings of this dissertation on the differences between blockchain systems and contemporary multi-sided platforms should not be interpreted as generalizable or exhaustive descriptions. Instead, they should be viewed in the light of one explanatory framework for interpreting the observed differences between the two types of systems on a wider techno-socio-economic level.

5.3 Research question 3: Transformative impact

The sixth primary finding in this dissertation specified that the make-or-buy dynamics in blockchain platforms oscillates independently from contemporary multi-sided platforms. Through case studies and secondary interviews, Rajala *et al.* (2018) discussed the importance of increasing platform openness to enable intelligent closed-loop ecosystems. By analysing the market side governance structures in the Bitcoin cryptocurrency platform, Mattila & Seppälä (2018) pointed out the lack of governance in terms of more strategic platform goals. By improving the source code of a blockchain smart contract through design science, Hukkinen *et al.* (2017) underlined the scarcity of platform core resources and the necessity of each participant to optimize their use of said resources. By analysing conceptual case studies, Lauslahti *et al.* (2018) described how blockchain smart contracts can change the boundaries of the firm by enabling more extensive process automation and horizontal modularity in company IT processes. Furthermore, by applying semi-structured evaluation interviews to a design science solution proposal, Mattila *et al.* (2021) addressed some of the challenges in implementing a fully decentralized platform in the current industrial landscape, implying a need for a higher degree of vertical integration in real-world applications. Combined with Fine's double-helix perspective (Fine, 1996; 2008; 2010), these observations were synthesized to produce the sixth primary finding.

In the light of the findings of this dissertation, it is clear that blockchain platforms are not to be taken as substitutes for conventional multi-sided platforms—nor is their relevance to conventional business cases equal. Especially the scarcity of freely exploitable IT resources is something which at times has been overlooked, causing misconceptions about the phenomenon's strategic relevance. Thus, it should be acknowledged that this dissertation has not shown that blockchain platforms would be better choices in the gradient of configurations for multi-sided platforms—nor has it been the point of this endeavour. Instead, what the dissertation suggests is that blockchain platforms extend the potential gradient of multi-sided platforms and platform co-opetition further than before.

A synthesis of the research findings suggests that despite the low adoption rate and the challenges in implementability in conventional business processes, blockchain platforms may yet have an indirect transformative impact for the platform economy. At the very least, they provide an example of how the evolution from static value chain pipelines to dynamic multi-sided platforms can progress even further along the same tangent, leading to an even more significant transition away from the contemporary service-structured view, and towards an even more all-encompassing value co-creation perspective.

However, some contrarian viewpoints have been presented in the wider academic discussion regarding the transformative impact of blockchain systems. For example, in their white paper, Ketsdever & Fischer (2019) have argued that the problem faced by permissionless blockchain systems is that they must incentivize users to maintain the system, but at the same time they must prevent the centrification of power to a small minority. According to Ketsdever and Fischer, this dual problem cannot be solved by the internal protocol-level incentivization alone. Along the same tangent, Walch *et al.* (2019) has also called the decentralized nature of blockchain systems in question. In this regard, however, the socio-economic framework delineated in this dissertation allows the reframing of the question of the transformative impact of blockchain systems. From the standpoint of the blockchain double helix (see Figure 4), decentralization of the system is not placed as the key feature of the transformative impact, insomuch as the oscillation between the core and the edge—the spectrum of vertical integration and horizontal modularity.

5.4 Concluding thoughts

So, to return to the question put forward in the introduction chapter, did the blockchain technology cycle of the past decade inflict or instigate some kind of a digital transformation after all, despite the challenges in implementability and the lack of uptake in real world applications? On the basis of this dissertation, there are many ways in which this question could be answered. Firstly, it could be argued that the emergence of blockchain systems did not instigate a transformation of digital money because, despite its name, cryptocurrency does not appear to be analogous with conventional currency (see *e.g.* Grym, 2018a, 2018b). Instead, on the basis of the findings, it seems better characterized as some kind of an amalgamation of a digital substitute for precious metals, crowdfunding equity, commodity money, and platform-specific local currency, constituting a new speculative asset class essential to the inner workings of permissionless blockchain systems.

Secondly, one could state that the reason why blockchain systems did not inflict a disruption of digital trust is that—contrary to popular belief—they are not entirely trustless. On the basis of the research findings of this dissertation, blockchain platforms such as Bitcoin still seem to involve middle-men and aspects of social trust and external governance that cannot be mitigated by their algorithmic design. Moreover, in many cases, these hidden trust mechanisms seem—not more, but *less* transparent than those in conventional platforms. In this regard, expanding on the earlier discussions on digital trust by *e.g.* Glaser *et al.* (2018) and Söllner, Hoffmann, & Leimeister (2016), this dissertation also makes a contribution by highlighting the fact that mechanisms of social trust can be pinpointed in blockchain platforms, despite of their trustless reputation.

Thirdly, it could be said that the decentralized peer-to-peer nature of blockchain platforms did not disrupt the centralized platform incumbents, because the *de facto* nature and the benefits of the decentralization in blockchain platforms are not entirely clear. This conclusion also supports the earlier observations presented in academic discussion that decentralization is not automatically a superior design principle for digital platforms (see *e.g.* Cennamo, Marchesi, & Meyer, 2020; Walch *et al.*, 2019).

Fourthly, building on the first three points, in a way, one could also argue that in fact a transformation *did* occur, but in a manner that was largely misinterpreted due to poor choices of frames of reference. After all, as pointed out earlier in this dissertation, the most prominent blockchain networks, such as Bitcoin and Ethereum, constitute arguably some of the most powerful computing grids in the world—yet no contracts, formal agreements, or other traditional constituents of platform co-operation have been applied between the participants. Yet, these networks seem to behave in a platform-like manner, exhibiting indirect network effects and complementarities, as well as technical and social boundary resources in their effort to foster growth. Setting aside the question of social constructs (see Section 3.1.2), deploying an open source peer to peer collaboration of such magnitude would arguably have been technically difficult in the past, by any available means, for that matter.

From the perspective of the blockchain double helix, one additional consideration is of interest in regards to the transformative impact of blockchain systems. In the very recent years, as the digital platform giants, *e.g.* Facebook, have been faced with more antitrust policy tussles, some plans have been put forward for more decentralized solutions based on permissionless blockchain systems. However, while initiatives such as Facebook's Libra may have presented themselves as having decentralized aims on the surface, the question does arise, whether the ambiguity of the decentralization aspect in blockchain has provided a way for the digital platform giants to circumvent antitrust regulations. By seemingly moving towards increased horizontal modularity in the double-helix, blockchain platforms could potentially be exploited as enablers for predatory innovation (Schrepel, 2017, 2020).

6 Conclusion

This dissertation set out to explore whether permissionless blockchain systems could be delineated in a structured and comprehensive manner as *multi-sided platforms*. By applying a critical realist methodological approach, the dissertation examined public permissionless blockchain systems through a multitude of research methodologies and focal perspectives. Through the multi-sided platform framework and methodological plurality, the dissertation made an effort to elucidate the transformative value of blockchain systems in regard to the digital platform economy and digitalization in large.

The findings of this dissertation imply that permissionless blockchain systems can be described as multi-sided platforms. Differing from conventional digital platforms where the deployment costs are high but operational costs are low, blockchain platforms require low initial investments for deployment, but with the trade-off of more significant operational costs and capacity constraints. Indeed, blockchain platforms are not to be taken as substitutes for conventional platform, nor are they improved versions thereof. Rather, blockchain systems seem to represent a limited example of a transition from the conventional service-structured view towards an even more all-encompassing value co-creation perspective, more so than what is facilitated by contemporary multi-sided platforms.

In terms of the transformative impact of blockchain systems, this body of work suggests that a digital transformation of sorts has taken place in the past decade as a result of blockchain technology. However, this transformation seems largely misinterpreted due to poor choices of explanatory frameworks and overinflated expectations. Transcending the more popular perspectives rooted in decentralization, trust, and digital currency, this dissertation paints a picture of the transformation through a lens of platform deployment, vertical integration, and horizontal modularity.

While the dissertation does not show that all manifestations of blockchain technology constitute multi-sided platforms, it indicates that the multi-sided platform framework can be meaningfully applied to the examination of blockchain systems from a wider socio-economic perspective. By systematically linking the blockchain phenomenon to the comprehensive socio-economic framework of digital multi-sided platforms, this dissertation enables better and more comprehensive exploration of this transformation in the future.

Endnote

[1] <www.top500.org/lists/2019/11/> Accessed 7.2.2020.; <www.blockchain.com/fi/charts/hash-rate> Accessed 7.2.2020.

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Article 1

How Do Intelligent Goods Shape Closed-Loop Systems?

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Original publication:

Rajala *et al.* (2018). How Do Intelligent Goods Shape Closed-Loop Systems? California Management Review, Vol. 60(3), pp. 1–25.

Abstract

This article explores how disruptive technologies increase the intelligence of goods and revitalize business models in the circular economy. Applying the industrial ecology perspective, we discuss how intelligent goods can boost the sustainability of industrial ecosystems. North American and European cases highlight how business model innovators utilize goods-related information to develop more competitive closed-loop systems. We identify three archetypes of closed-loop systems—inner circles, decentralized systems, and open systems—and delineate how they leverage information resources for collaboration. This study advances the understanding of closed-loop systems in the circular economy, which is more dependent than ever on digital platforms.

Keywords

circular economy, environmental protection, green manufacturing

1 Introduction

A growing body of research has drawn attention to value creation in closed-loop industrial systems,[1] because environmental concerns are pressuring organizations across industries to rethink their business models.[2] In addition, the ownership, recycling and sharing of material resources are taking new forms with the rise of the circular economy. Closing industrial loops by making better use of raw materials and by turning waste into energy and components for refurbished goods contributes to environmental sustainability, and provides new business opportunities for industrial actors. For example, conflating ownership of goods with ownership of the intelligence in goods opens up the space for novel business models in smart manufacturing. Consider our findings from Canadian supply chains: the virtuous cycles of circular economy are built on both green production and green supply chains.[3] Furthermore, the findings indicate how tracking the provenance, sustainability and ownership of goods and material in addition to ensuring the profitability of supply chain actors are crucial activities, given that firms depend on resource and capital efficiencies while customers are paying more attention than ever to the provenance of goods and the ways that firms buy or license replacements. The circular pathway is a more sustainable way for a society to continue prospering without exhausting primary materials and energy. It is possible by reducing waste in production and consumption of products, especially closed-loop recycling. To illustrate, more than 80 percent of all copper ever mined is still in circulation today.[4] The changes in the notion of ownership of goods and information would accelerate further considerations in relation to sustainability.

Goods are increasingly equipped with computing and data processing capacities that enable handling and storing of information about their real-time condition, location, operation, use, history and the surrounding system in which they are used. The embedded intelligence enabled by information, software and hardware transforms products into active nodes of new value-creating systems. Moreover, the rise of the circular economy transforms goods-focused businesses into service- and platform businesses; it is changing the ways in which information sharing and market transactions take place. Although the increasing intelligence of goods, the resulting information intensity of services, and the impending shift to digital platform-enabled transactions[5] have attracted considerable research attention, there is little empirical work on the collaborative practices of utilizing information resources and objects in business ecosystems of the circular economy. This is a critical gap in the knowledge, because firms in technology-enabled business ecosystems need to play an active role for the circular model to work. Just as the use of raw materials is important for production, innovative firms must develop new industrial systems and practices for sharing information and make use of the information related to circulated materials and products. For closed-loop value creation to be productive and sustainable, it is necessary to widen the consumption of goods by extending their longevity and by reconsidering ownership issues. For such goals, information about the goods plays an essential role.

To fill this gap in the knowledge, we explore *the ways in which the intelligence of goods influences closed-loop ecosystems*. In so doing, we extend the discussion of firms' competitive behaviors by adopting the perspective of industrial ecology to illustrate how companies collaboratively utilize resources and capabilities within their networks based on their context-specific needs.[6] We suggest that the growing intelligence of goods as well as the growing autonomy of programmable devices are generating novel constellations of value creation and capture. In brief, intelligent goods enable distributed and open ecosystems, whereas less-intelligent goods are associated with centrally governed operations, because fewer actors in the closed-loop ecosystem manage the intelligence apart from the good.

Based on insights gained through our extensive empirical research, we conceptualize the archetypes of closed-loop systems as inner circles, decentralized systems, and open systems. These archetypal systems exemplify different approaches to collaboration, the management of information resources, and innovation for sustainable recycling. Moreover, we show how these circular models utilize disruptive technologies in their business models and highlight the role of intelligent goods in creating value with services in which the value is not measured or experienced in terms of physical assets. In so doing, our study highlights the role of intelligent goods in shaping closed-loop systems.

Our findings underscore that, for closed-loop systems to sustain themselves, firms must step away from focusing exclusively on the flow of goods and instead reconsider their roles, responsibilities and complementarities by using goods-related intelligence in the new industrial systems. This shift in focus is increasingly important considering how the traditional thinking of markets, assets and value propositions, which draws upon the resource-based view of competition, may lack the emphasis on reducing inexhaustible material and energy flows. For example, Kenneth Boulding vividly depicted this traditional thinking as the "cowboy economy" to underline the reliance on continuous supply of new material resources.[7] It is reasonable to suggest that material intelligence and more effective management of information related to goods will contribute to the rise of the circular economy through a healthier balance of material and energy flows.[8] The circular economy does not only mean corporate sustainability or green strategies. It also requires the creation of trust among business partners and the development of new practices of sharing information and utilizing resources by plugging potential structural holes[9] in the emerging business ecosystems.

The rest of this article consists of two sections. In the first section, we explain how the intelligence of goods influences closed-loop systems. In the second section, we discuss how the three archetypes of closed-loop systems leverage sustainable recycling through different platforms for collaboration, different methods of managing information resources, and unique approaches to innovation.

2 How does the intelligence of goods affect closed-loop ecosystems?

With intelligent non-durable, durable and capital goods, fluent information exchange between nodes and organizations in diverse business ecosystems is crucial. While technological disruptions of information exchange create opportunities for value creation and capture, they can also create structural holes to existing and emerging industrial systems. That is, new capability and information gaps arise where the current ways of exchanging information among the actors fail to meet the actors' evolving business needs. A new actor may assume an integrative role to close the gap, and they may subsequently plug the structural hole. Therefore, a structural hole can also be considered a source of innovation as third-party actors[10] become aware of alternative ways of thinking and behaving in industrial systems, thereby generating new options to meet the other actors' evolving needs.[11]

Innovations that plug the structural holes exhibit technology and knowledge brokering. Thomas Edison's innovation factory became famous for products that blended existing but previously unconnected ideas and technologies and brokered this knowledge from one industry to another (Hargadon & Sutton, 1997, 2000). For this purpose, Edison's factory constructed a network rich in structural holes that afforded speedy access to diverse information sources. However, the benefits of structural holes depend on the context (Ahuja, 2000). Put differently, having more structural holes in a network is not necessarily better, despite the breadth of ideas that those holes might generate.

Networks with many structural holes can lead to situations where each party pursues their own individual goals. In other words, a high number of structural holes in a network promotes actions and strategies that uphold rivalry and segregation between the parties.[12] Therefore, when developing a collaborative milieu, it is useful to plug structural holes to create a denser network. Plugging leads to a more cohesive group of interconnected partners through increased trust, improved collaboration routines, and reduced opportunism.[13] Because of these advantages, new technologies that help closing structural holes are especially important in facilitating circular ecosystems.

Closed-loop systems can be considered as business ecosystems that take shape to create value for the actors involved. The literature on industrial ecology is concerned with the ways in which the industrial economy and the environment coexist at both the levels of firms and individual actors operating in a system. Mathews and Tan (2011) emphasize the importance of the identification and analysis of many "eco-industrial initiatives" that reduce the energy and resource intensity of industrial activities. Traditionally, industrial actors have pursued harmony between the industrial economy and the environment by using resources more efficiently, and by converting wastes from one process into inputs to another industrial process to increase productivity. We suggest that information about materials, knowledge of goods in their contexts of use is increasingly important in gaining such benefits. Moreover, material intelligence and the intelligence of goods may contribute to creating and maintaining the balance between the organization and the environment.

2.1 Material intelligence enables industry-wide business ecosystems

Jeff Curie, CEO of Bitvore, a new business intelligence venture, defines "material information" as information that matters to the users and producers of a product.[14] In short, it is information that has a "material" impact. Of course, "intelligence" is about insight, information and data. Thus, material intelligence provides customers with personal and contextual information about the materials they use to meet their business needs.[15]

Case 1: The steel industry

Pearlite[16] is a globally operating steel industry giant that specializes in processing raw material to produce steel. The company has a strong focus on discovering how to make its products more intelligent. It is investigating the idea of "steel as a message carrier." This means that Pearlite's steel products, identical pieces that conform to a given standard, become unique. The uniqueness of the pieces is a milestone en route to Pearlite's larger goal of "material intelligence." Pearlite's vision of material intelligence is to assign highly detailed properties to their products in order to automatize and optimize its customers' processes. In light of this vision, one Pearlite's director emphasized how its customers seek materials for "higher-quality products, less wastage, and more accurate audit trails." In turn, this comprehensive audit trail would accumulate information to guide Pearlite's future product development.

Material intelligence and the audit trail it enables have tremendous value potential in the steel industry. Giving the material a digital identity enables a new world of potential innovations. In addition to the considerable benefits at the recycling phase, the digital audit trail provides a way of observing the full lifecycle of the material. Our findings from Pearlite show that new types of industry platforms have considerable potential in facilitating product-related information flows to align the needs and requirements of different actors, given that "more direct collaboration will help us develop products that bring value to our customers" (Service Director, Pearlite). Similar observations across industry actors indicate a paradigm shift from a strict supplier–customer relationship toward a more collaborative approach involving product-related data sharing in the industry. Different actors that have access to the audit trail can provide innovations that can alter the way that the product moves through the loop and what kinds of material reuse systems become possible. The audit trail would enable material reuse systems suggested by Ness and colleagues (Ness *et al.*, 2015) without the need for add-on sensors or monitoring devices.

Managers at Pearlite perceive the virtual characteristics of goods as opportunities to enable the formation of platforms that combine the physical and information aspects of products with service-based value creation. Such platforms comprise an important inter-organizational structure that facilitates information flows among actors and processes, thus plugging the structural holes in the networks. Shared information helps to optimize and automate the supply chain processes, and to identify new uses for the accumulated data. Executives at Pearlite see that the unanticipated connections and uses of data have the potential to surpass the role of any preplanned information exchange. Therefore, their vision of material intelligence relies on considerable openness.

2.2 Digital platforms foster collaboration in closed-loop ecosystems

Most literature on digital platforms focuses on the disruptive potential of technology (Gawer & Cusumano, 2014). For traditional businesses and industries to move toward platform-enabled value creation and capture, they must look beyond the hype about disruptive technology and realize that sensors, telematics, machine-to-machine (M2M) and other technologies are just the nuts and bolts. What really counts is the intelligence that will hold these important technologies together using the infrastructure—the services, the apps, and the technical boundary resources and objects—and with this business model disruption come new ways to create value and innovations (Mejtoft, 2011).[17]

Case 2: Waste management

Rubicon Global, founded in 2008, has set out to change the waste management and recycling industry. Traditionally, waste management companies have made money by collecting trash. Some companies do attempt to recycle waste, but there is little incentive to do so.[18] Potential revenues from costly recycling are shrinking due to plummeting oil prices, which means more waste in landfills. Rubicon has flipped the industry's revenue model and the incentives for recycling while striving to be entirely green: the aim is to reduce the amount of waste going to landfills and cut down unnecessary pickups while making profit.[19] Rubicon's model is "less waste, more money," making its approach to garbage management the polar opposite of that of traditional waste management companies. How was this possible?

Rubicon does not own any landfills or garbage trucks. It is a facilitator or marketplace between companies wanting to cut their waste costs and local haulers who can bid on jobs. Rubicon also controls the system in a way that avoids unnecessary pickups. Then, Rubicon analyzes the waste and sells off what it can. The revenue comes from two sources: first, whenever a company manages to make savings, Rubicon takes a slice; and second, whatever Rubicon can sell for recycling does not end up in landfills and makes more money for Rubicon.

A software platform controls everything in this new model. Essentially, Rubicon is a technology startup that is attempting to renew a mature industry. Information is key in Rubicon's service operations: they use it to optimize everything. Rubicon is still a small player in the field, but it will be quite exciting to see how such initiatives can transform the waste collection and disposal industry. So far, it has been fascinating to see how Rubicon has aligned the client's corporate interests, Rubicon's own interests, and the broader environmental interests. However, much still remains unexplored. Rubicon's co-founder Morris Moore said[20] that fully exploiting the data collected from companies could be the most valuable part of the whole setup.

2.3 Intelligent nodes enable the harnessing of distributed networks for value creation

Approximately 98% of the world's processors are not in personal computers but embedded into diverse cyber-physical systems[21] that combine virtual and physical worlds. These systems enable new types of closed-loop ecosystems that make use of distributed ledger technologies, such as blockchain technology popularized by the Bitcoin cryptocurrency. Distributed ledger technologies make a great example of systems that bear the characteristics of commonly owned information in peer-to-peer (P2P) networks. Distributed ledger technologies are methods by which parties previously known and unknown to one another can jointly generate, maintain and share practically any database on a fully distributed basis. Each party receives a copy of the ledger (or part of it) and may then make changes to the database subject to collectively accepted contractual and business rules.

Case 3: Automotive batteries

Our study of automotive batteries puts the spotlight on recycling in ecosystems built on intelligent goods. The popularity of electric cars has suffered from the long recharging time relative to the distance they are able to travel on a single charge. Stringham, Miller and Clark suggest that a network of actors can rectify this shortcoming by introducing a systemic change to the value system (Stringham, Miller & Clark, 2015). In 2013, Tesla introduced a service concept for electric cars, replacing the rechargeable battery pack with a fully charged battery at a service station.[22] If the market adopts such a flat-for-full swap solution, and the batteries include adaptable microcircuits and necessary technical boundary objects and resources, the intelligent battery concept could benefit from using the distributed ledger technologies in the following ways.[23]

The intelligence of goods enables new types of transactions in business ecosystems. When a customer leaves the battery at a service station for recharging, the battery connects to a P2P network autonomously created by the smart components involved. Next, the battery starts gathering information on, for instance, the supply and demand of electricity, battery stock levels at the nearest recharging stations, amount of road traffic, and the status of each battery within the current operating range. Having collected all this information, the battery then performs a trend analysis: whether it would make economic sense to buy electricity at the local station and recharge itself right away or to sell the power it still retains to some other party and wait for the market price of electricity to fall.

The node is also capable of performing business intelligence. To carry out trend analysis, the battery may, if necessary, buy additional computing power or any other resources from other goods, such as batteries waiting to be recharged, the drinks vending machine at the station, or a robot vacuum cleaner, that are not using their built-in processors for other tasks at the moment. The battery will look up the supplier offering computing power at the lowest rate in the exchange jointly created by the smart components with the help of the distributed ledger technology enhanced with technical boundary resources and objects. The battery pays compensation for the computing power from its device-specific account to the accounts of the other devices by using, for instance, cryptocurrency.

Once fully recharged, the battery will reconnect to the marketplace generated by the components and start marketing itself to other vehicles in the vicinity that have compatible but low batteries. Moreover, the battery can offer itself to vehicles whose batteries were charged at a higher cost. If the driver accepts the offer and leaves the more expensive battery at the station, the difference between the battery and the vehicle is settled in cryptocurrency, and the vehicle will continue its journey with cheaper electricity. The battery may offer itself at a loss if there is a risk of being stuck at a remote station with little traffic. Another possibility is that—as long as the components are mutually compatible—the battery can offer itself for use in other assemblies, such as small-scale power plants or households that are a part of smart microgrids or nanogrids.

Once the battery has accumulated enough profits on its device-specific account, it will order servicing for itself and pay for the service from its account in cryptocurrency. If there is any surplus profit after all the operating costs, the battery will credit the difference to the company that owns it. In between the payments, the owners will not need to pay any special attention to the battery because it transacts business fully autonomously as if it were a subsidiary consisting of a single component. As a result, there would be no need for costly centralized cloud services or other background processes designed for millions or even billions of batteries. Instead, each battery would buy the products and services it needs from the most affordable supplier autonomously at a given time.

Intelligent goods can be designed for recyclability. For example, at the end of its service life, a battery puts its recycling out to open tender and pays for it from its earnings, ensuring that the customer or company incurs no expense for disposal. As its final action, the battery will credit any “inheritance” left to the company that owns it. The tasks that the intelligent node was programmed to accomplish form a distributed, autonomous network for a platform-enabled business ecosystem. It differs from the decentralized network of the steel industry case not only by the structure of the network, but also by the rules of the value creation and capture. Yet, it is possible to apply distributed ledger technologies to Pearlite.

2.4 The increasing intelligence of goods raises the issues of information management and data ownership

Information intensity inside non-durable, durable and capital goods, supply chains and nodes is bound to increase. In many industrial fields, the increased information intensity links with the transformation of industrial firms’ strategies towards service-based value creation, because addressing customer needs calls for more complex offerings than ever. In other words, many firms are moving from sellable products to service-based value creation. Moreover, given the growing role of technological platforms for multi-actor collaboration, more actors are sharing information about goods. Along with the growing intelligence of the goods, the role of information management in value creation is increasing.

Along with the increasing intelligence of goods, the importance of access versus ownership of data becomes an increasingly complex and debated issue. Our empirical findings indicate that, in general, the possession of data may become less important, whereas the capability to utilize the available context-specific information may become ever more valuable. Even though an organization may have *de facto* control of data, it can only claim its ownership if it is entitled to do so in the legal sense.[24] For example, facts and statistics collected for reference or analysis can be stored and managed. A traditional view of information management is that the organization possesses the infrastructure, such as goods where the data are stored (Wade & Hulland, 2004). The ownership of goods is the default assumption in data management when organizations have not made and executed contractual arrangements or the like. In this case, the owner of the goods usually has a natural ability to prevent others from accessing the data by blocking access to goods. Furthermore, within the freedom of contract, the parties can specify to whom the information belongs, what kinds of access rights there are to the data, and whether these rights are exclusive or parallel.[22]

Nonetheless, many supply chain actors, such as suppliers, manufacturers, distributors, service providers and financing institutions, have their own interests in managing both the information related to goods and consumers in different compilations. These interests can entail barring others from accessing the information through the lifecycle of the goods. In addition, a party has ownership-like administration of data when it has the ability to deny other parties the use of the data even when it does not have actual ownership (Thurow, 1997).

Intellectual property rights for intangible assets, such as information, however, enter the stage only when someone uses information for specific purposes, for example, as part of an innovation process. For the future, information produced in service encounters as part of the supply chain activity in digital platforms needs to be considered in the same way.

2.5 Distributed ledgers pepresent important infrastructure elements in closed-loop systems

From the perspective of intelligent goods, the reliability and accuracy of information will be increasingly significant. Trust and accountability will shape contract policies between parties given that information flows through different interfaces among the actors. Considering the length of the transmission chains, it must be contractually possible to establish the causality of liability. In distributed ledgers, however, there are no lengthy information-transmission chains; rather, the liabilities are shared between the organizations. In the end, the contract and business rules of distributed ledgers will define the strengths of shared information ownership between parties. Furthermore, solutions are being developed where data encryption enables untrusted parties to store, manage and share sensitive information without compromising its privacy (Mattila & Seppälä, 2015; Zyskind, Nathan & Pentland, 2015).

A distributed ledger is a key infrastructure element for a P2P network in which organizations can store, manage and share information to form one data structure of any good (Eisenmann, 2008). In a permissioned ledger, one organization possesses the authority to permit or prohibit the participation of other organizations to access and/or to edit the data in the distributed ledger. Conversely, in a permissionless ledger, any party, known or unknown to the other participants, is free to access and edit the data in the ledger, as long as it complies with consensus rules mutually agreed upon by the participants. The participating organizations store, manage and share information in a joint fashion according to a tamper-resistant set of verifiable contract and business rules, backed up by hash functions and cryptographic algorithms.

3 How to leverage different closed-loop systems for value creation

Table 1 introduces three archetypes of closed-loop ecosystems and summarizes their distinctive characteristics. We label these archetypes as "inner circles," "decentralized systems," and "open systems."[25] Based on our observations of a large number of closed-loop ecosystems, we explicate their characteristics in Table 1.

Table 1. Composition of closed-loop ecosystems: A synthesis.

ARCHETYPES OF CLOSED-LOOP ECOSYSTEMS	INNER CIRCLES	DECENTRALIZED SYSTEMS	OPEN SYSTEMS
EXAMPLE	STEEL INDUSTRY	WASTE MANAGEMENT	AUTOMOTIVE BATTERIES
	PLATFORMS FOR COLLABORATION		
ECOSYSTEM STRUCTURE	▪ Cross-sectoral partnerships	▪ Multi-centric industrial systems	▪ Marketplaces
INFORMATION EXCHANGE RELATIONSHIP	▪ Longstanding, relational exchange among business partners	▪ Tightly coupled industrial systems for data sharing, and an extensive system of systems in which new and existing actors learn to utilize the data.	▪ Market-based, transactional exchange. Enables anybody to execute practically any interaction requiring mutual trust electronically without intermediaries.
PLATFORM TYPE	▪ Internal and supply chain platforms supporting business collaboration	▪ Supply chain platform enabling a multi-actor production system	▪ Industry platform, a new infrastructure for transactions
	MANAGEMENT OF INFORMATION RESOURCES AND OBJECTS		
ESSENTIAL INFORMATION	▪ Goods-related information	▪ Data collected to optimize resource efficiency in the system	▪ Situational knowledge
LOCUS OF INTELLIGENCE	▪ Associated with, but distinct from goods and material	▪ Some level of intelligence at objects (e.g., transceiver capabilities) supported by external network	▪ Located at the object
DATA OWNERSHIP AND MANAGEMENT OF BOUNDARY RESOURCES	▪ Shared data repositories. Access to data maintained collectively with boundary resources.	▪ Controlled by a third-party actor. Shared practices and technology to access and share information.	▪ Distributed, accessible by publicly auditable rules. Programmable interfaces as a key boundary resource.
	INNOVATION FOR SUSTAINABLE RECYCLING		
DRIVERS FOR CHANGE	▪ Product commoditization	▪ Optimizing current processes	▪ Disruptive innovation
VALUE CREATION LOGIC	▪ Collaborative value creation	▪ Multisided market, stakeholder groups hold their own interests	▪ New dominant design, new actors
INNOVATION FOCUS	▪ Evolutionary supply chain innovation	▪ Ecosystem-level ambidexterity	▪ Revolutionary, systemic innovation

3.1 Platforms for collaboration in closed-loop ecosystems

Platforms and distributed ledgers may become essential drivers for closed-loop ecosystems. The structures of collaboration in closed-loop ecosystems range from cross-sectoral partnerships to multi-centric industrial systems and platforms that enable marketplaces for transactions across the lifecycle of an object. The research is still inconclusive on how platform ecosystems emerge and create benefits. Although there are different classifications for platform types,[26] it is difficult to categorize all platforms.

Based on our observations, different types of platforms have alternating logics for value creation. The steel industry case underlines the potential for cross-sectional partnerships to create innovation leverage:[27] different actors expect collective benefits that may materialize in the seemingly distant future. In the meantime, the companies would develop a collaborative ecosystem by opening their internal platforms to their partners, thereby insulating themselves against outside competitors. The Rubicon case exemplifies how multisided markets can create production leverage—they optimize existing processes, generating value to each participant and reducing waste, all the while allowing Rubicon to take its share of the gained profits through its supply chain platform. Rubicon is constructing a multi-centric industrial system designed to allocate resources more efficiently. In the case of automotive batteries, autonomous intelligent nodes enjoy a considerable transaction leverage in the proposed marketplace. The marketplace can simultaneously help consumers to find the optimal solution to their needs and help providers to find the best possible market deal.

Platforms create shared value and benefits for the participants through network effects. The indirect and direct network effects of platforms can increase exponentially with the number of actors in the platform, providing potential for innovations and increasing the appeal of the platforms.[28] However, monetizing platforms is difficult because openness is what helps to grow the platform but control is what helps the platform owner to capture profits. Our cases present three different logics to address this duality. Pearlite protects its business against outside competitors by developing longstanding information exchange partnerships within its business network. Because collaboration evolves and improves over time, the existing partnerships are soon preferred to new entrants. The network level of control is high on the outside, but low on the inside. In turn, Rubicon has adopted an integrating role in its network, balancing openness with control. The network grows as its members become receptive to new entrants and actor role changes, but at the same time they control the information flow, ensuring a share of the profits. Finally, open systems have minimal control but strict policies. The system for automotive batteries is open to new participants that are willing to obey the rules. This openness results in a marketplace in which the automated and fluid exchange of information is commonplace.

Boundary resources that permit organizations to share and use shared information are vital for the creation of collective value in platforms. We conducted a survey of the boundary resources that enable firms to participate and enable participation to their digital platforms and ecosystems (Appendix 1). According to the findings, almost half of the firms in the technology industries have an application programming interface (API), including a set of programming instructions and standards for accessing a software application or a multi-actor platform.[29] In addition, about a quarter of the surveyed industrial firms have published a software development kit to enable external developers to make applications to the platform. Moreover, almost 20 percent of firms have published scripts (i.e., programs or sequences of instructions for external programs) to provide some complementary functionality to a platform.

As platform interfaces become increasingly open, more agents will be attracted to the platform ecosystem. Standardization of boundary resources, a central feature of genuinely distributed systems, will create virtuous cycles that boost the benefits to current participants and increase the appeal for new entrants. Making use of such resources enables actors in the platform to leverage the resources from others, thus increasing the potential for innovation, novel production scheme improvements, and efficient transactions. Hence, boundary resources are key components of a thriving closed-loop ecosystem.

3.2 Management of information resources and objects in closed-loop ecosystems

Closed-loop value creation raises the question of managing the intelligence of goods and goods-related information. To date, consumers connected through complex social and functional platforms have driven digital productivity, particularly information sharing. Industrial firms have fallen behind in this development. However, the new constellations for value creation build on activities between supply chain partners and organized data. Firms digitize, collect, organize and share data and content for them to be part of the new systems that create value through services based on information resources (Seppälä & Kenney, 2011).

Administration of information resources varies in different archetypes of closed-loop ecosystems. In the inner circles built for recycling, the key managerial concerns involve governing the goods-related information to enabling the use of the object in the next phase of its lifecycle. In decentralized, multi-actor systems, specialized actors add value to the value chain processes by making new connections among the object-related data and actors that may benefit from that data. In open systems working as marketplaces, the essential information determines the current situation and constraints leading to decisions on whether a node should buy or sell its assets. Sharing and utilizing information resources is the key for service-based value creation in all archetypes of closed-loop ecosystems. Technical boundary resources and objects, but also contract and business rules, become even more important when implementing permissionless distributed ledgers. By providing publicly auditable boundary resources and objects, the ecosystem could benefit from innovation activity for larger indirect and direct network effects.

The locus of goods-related intelligence varies among the types of closed-loop systems. As described in Table 1, the intelligence related to goods may be distinct from the goods and materials. Alternatively, some intelligence may reside in the objects operated by the external network. In the intelligent nodes that form distributed networks, intelligence may be located in the object. Concerning material intelligence in the ecosystem, smart instances can carry messages in the supply chain and enable value creation through service. By knowing the history of the instances, actors can better configure their own operations. Product and service instances possess a globally unique identity. Based on that identity, actors can handle the instances and retrieve information on, for instance, the exact composition of the item, process parameters of previous actors, and processing and sorting instructions, in addition to contextual information such as location.

3.3 Innovation for sustainable recycling in closed-loop ecosystems

Innovation for closed-loop value creation puts the spotlight on the sustainability of the business models in the ecosystem. Although material recyclability is an important condition for the sustainability and profitability of closed-loop value systems, it is not sufficient for sustainable value creation in the circular economy. The entire ecosystem must be favorable to innovating the participants' business models related to sustainable recycling. This view shifts the focus from recycling material to creating value with goods-related information.

Managing self-reinforcing cycles for recyclability calls for courage to iterate with an ecosystem-level business model. Thomas and colleagues[25] suggest different types of collaboration platforms to exhibit different innovation approaches and architectural leverage in terms of technology architecture, activity architecture and value architecture. In our synthesis of distinct closed-loop ecosystems—inner circles, decentralized systems, and open systems—the value creation logic builds on collaboration with trusted partners, thereby bridging the structural holes in the multisided market and adopting new dominant designs, respectively. For these purposes, the underlying multi-actor platforms manifest evolutionary innovation of the supply chain, optimization of the multi-actor production system, and revolutionary innovation of the supply chain to revolutionize the entire transaction logic of the ecosystem.

Sustainability innovation takes place at both micro (company) and macro (system) levels. In a broad view, micro-level sustainability innovation by companies should link with the macro-level sustainability innovation and its effects within society (Gaziulusoy, Boyle & McDowall, 2013). A micro-level innovation can result in systems innovation, which refers to the renewal of the socio-technical system (i.e., a set of networked supply chains, patterns of use and consumption, infrastructures and regulations) (Smith, Voß & Grin, 2010). In a narrow sense, sustainability innovations are inherently systemic and require ecosystem collaboration, although they consist of enhancements within one organization. Berns and colleagues suggest that companies pursuing sustainability innovation will need to develop the ability to operate on a system-wide basis and collaborate across conventional internal and external boundaries (Berns *et al.*, 2009; Smith, Voß & Grin, 2010; Rohrbeck, Konnertz, & Knab, 2013). Yet, business model innovation depends on the structure and characteristics of the closed-loop ecosystem.

3.4 Synthesis of findings: propositions for further research and management of closed-loop systems

The findings from our cases indicate that productivity increases will follow from work and process improvements and process reorganization rather than from technology innovations per se. For example, in Pearlite, the steel company, the innovation focus will move from IT systems to firms, teams and individuals who redesign their roles and responsibilities in the industry system by choosing the best supporting applications and proposing new ways of organizing value creation in their business networks. Based on our findings from the investigated cases, we establish four propositions concerning the influence of intelligent goods on closed-loop systems.

Proposition 1: *Traceability of things by means of documented and recorded identification revolutionizes resource management and material recycling in manufacturing.*

Information about the provenance of an object is a key resource for enhanced sustainability. Hence, data management and sharing play crucial roles in closed-loop ecosystems. New supply chain practices call for novel approaches to managing goods-related intelligence. To illustrate, "additive manufacturing" builds on the use of recycled raw materials in the local production of components by means of novel manufacturing technologies such as 3D printing. Such activity requires ample information to be shared and new types of transactions to be conducted among the actors in the production system.

Similarly, ecosystem-level traceability is in the locus of material intelligence. Our findings indicate that effectiveness in the micro-level management of items across their lifecycle phases will cumulate macro-level benefits in the ecosystem-level competition. Consider Pearlite's platform to record and maintain the production history of each steel plate in their production line. By providing each plate with a unique identity, all secondary producers can track the items and retrieve information related to them throughout the lifespan of the products. This capability can facilitate value creation throughout the ecosystem and revolutionize material management on the ecosystem level.

Another example is "remanufacturing," in which old parts are remade and restored to near-new conditions for new deployments (Abbey *et al.*, 2015). In addition, new types of ownership of goods make the third example: an increasing number of organizations provide goods as a service and charge the customer per operational hours of the goods. This approach necessitates an extensive knowledge of the goods in their contexts of use. It can lead to sharing of the ownership of the goods throughout the lifecycle, among all supply chain participants, based on their value-added contributions.

Proposition 2: *The increasing intelligence of goods dilutes the importance of the ownership of things.*

In the future, the concept of ownership will have to be redefined. Ownership in closed-loop systems is different from ownership in traditional supply chain constellations. The meaning of ownership has traditionally been broad, encompassing the acceptance of liability and responsibility for product life, accountability for errors, the taking of responsibility for malfunctioning, quality, taking initiative, and making independent decisions about matters delegated to the owner of a resource in a supply chain. In contemporary closed-loop ecosystems, actors are responsible for these issues to the next party and finally to the end customer when selling the product. If ownership over the product stays with the manufacturer until the end of its lifecycle, a realistic outcome of such a transformation would be the servitization of all the things. Similarly, it is possible to provide materials as a service.

As intelligence of goods makes its way to a variety of contexts, products might soon include many components that are intelligent on their own. In an information-intensive context, it is possible to share the ownership of the data or the thing across all participants in the supply chain. Alternately, it is possible to separate the ownership of the product from its data even if each participant chooses to retain the ownership of their data.[30] One of the drivers for sharing product data, as shown in the Pearlite case, is that participants strive to add their own value to the final product and maximize their share of the created value in the ecosystem. Alternative constellations in the product and data ownership affect value creation processes in different ways.

Our cases offer three examples of the potential ownership logics within closed-loop ecosystems. Inner circles, such as the steel industry ecosystem, can function with a traditional transaction-based chain of ownership or with a leasing model where functionality comes as a service. However, in both cases, the ecosystem has a collective attitude towards the ownership of information resources. Actors such as Pearlite might have a leading role in initiating the data sharing in the ecosystem, but the value creation relies on collectively shared data that is accessible to all the participants. Conversely, decentralized systems manifest logics where a central operator brokers the information flow and facilitates the value creation over its multi-sided market. In waste management, Rubicon collects items discarded by their previous owners, thereby gaining ownership of those items. It may not gain access to historical data, but henceforth controls data management. Last, open systems go the farthest in challenging the inherent assumptions on ownership of goods. With open marketplaces, we may see constellations where "things" equipped with intelligence and smart contracts become self-sustaining entities. Such things participate in open markets, form contracts when they see fit, and make decisions that affect value creation.

Proposition 3: *Smart contracts that enable algorithmic transactions between objects become crucial boundary resources for actors in closed-loop ecosystems.*

Boundary resources are the opposite of entry barriers. They lower the traditionally high costs of development and commercialization that are usually associated with bringing innovations to the market. Digital platform providers benefit from providing third parties with access to their boundary resources through split revenue models. By under- and overcharging different market sides according to their willingness to participate in the platform ecosystem, platform providers can foster network effects and maximize profits. Providing the market with openly accessible boundary resources is a difficult decision for companies that do not own their manufactured products in the contemporary supply chains. Moreover, this approach can be problematic in terms of closed-loop ecosystems, because relinquishing ownership most often also translates into forfeiting control over the product.

However, well-functioning boundary resources enhance value creation in ecosystems. Consider Pearlite and material intelligence in the steel industry: an insurance company may provide a less expensive coverage to a product manufactured using better raw material if it knows where the material originated. Ultimately, the end user will yield a better recycling compensation for items with a known composition. Knowing the exact composition of the scrapped materials eases the forming of ideal composition in each batch, thus making the process more affordable. In addition, the alloying elements are often very valuable on their own. In some cases, they are even more valuable than the recyclable bulk material (Van Beukering, Kuik & Oosterhuis, 2014). Therefore, the more efficient recycling process with more refined material streams would be beneficial in many ways, as it leads to a higher value of the product for each actor in the value chain, including the original producer.

One of the latest developments in distributed ledger technology, "smart contracts," allow for parties distrustful of each other to store and execute shared programming logic in a completely distributed fashion. Such contracts enable actors to maintain a consensus not only over who owns which assets, but also on the rules and the agreements on how individual assets should autonomously behave and interact in the future.

Casey Kuhlman, the CEO of Monax Industries—a startup operating in the field of smart contracts—has said that "[s]mart contracts provide the backbone for automating business processes which reach *outside* of the rotating glass doors" (Monax Industries, 2015). Furthermore, in a recent Forbes interview, Don Tapscott, a business strategy expert and an author on distributed ledger technology, stated that smart contracts will profoundly reduce contracting costs outside the boundaries of the corporation, in reference to the transaction cost theory by the Nobel Prize-winning economist Ronald Coase (Shin, 2016).

Through these smart contracts (i.e., self-executing and self-enforcing computer programs stored in a distributed peer-to-peer network), actors can commit their assets to certain behaviors in the presence of pre-determined triggering events. Smart contracts would enable manufacturers to design and program their products to function as a part of a closed-loop ecosystem from the moment they are built until the last moment of their lifecycle.

Proposition 4: *Resolving the challenge of digital trust will enhance the productivity of conducting transactions on goods in closed-loop ecosystems.*

Over the lifecycle of a product, many parties need to use and manage the data related to a product or a service. Because value creation by multiple actors in a platform-based collaboration is becoming commonplace, the question of digital trust is of fundamental importance. Actors must be confident that the parties involved are who they say they are and that they will do what they promise to do. Without trust, the potential for benefiting from closed-loop systems of any kind is quite limited—no matter how interoperable the relevant systems are.

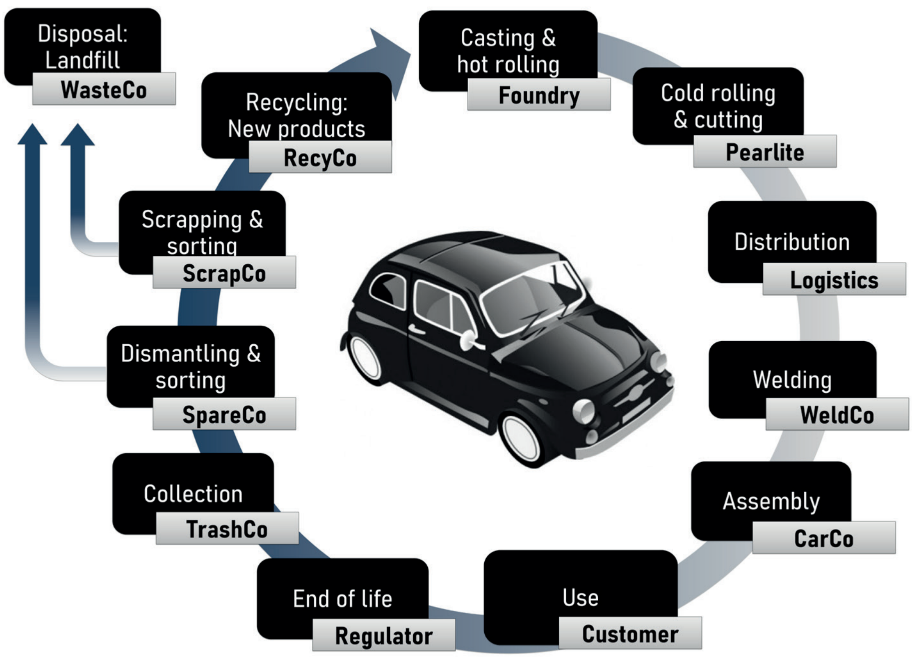
Distributed ledger technologies enable the creation of a new type of digital trust where no individual party needs to be trusted to guarantee database authenticity. Instead, all that is required is trust in the fact that most of the actors are behaving honestly in the network. Policy makers have an important task to enable smart transactions among actors possessing identities verified through distributed ledgers. In this regard, trade legislation should strictly enforce contractual obligations between nodes and intelligent products in the network, whereby the distributed ledger technology can significantly enhance the productivity of closed-loop ecosystems. The emerging closed-loop ecosystems will eventually do so by guaranteeing safe and secure autonomous transactions between products and services from different companies.

4 Conclusion

The three archetypes of closed-loop systems employ a distinctive digital platform that merges the physical and digital worlds of material and goods management in the system. Within this fusion, central factors require management if the investments in closed-loop value creation are to generate profit. What remains is harnessing the data to create new value opportunities for the business, thereby rooting the business models in the intelligence of the ecosystem activity at the level of resources. Even though the technology collects and exchanges data between other devices, the company's employees and ecosystem participants need to understand how to use this data before they generate value and become an essential part of a closed-loop ecosystem. Simply improving the resource efficiency of supply chains will not be enough. We need to answer the question: "What really matters?"[31]

Our empirical cases provide managers with insights into the influences of intelligent goods on the structural configurations of closed-loop systems across industries. For example, as the literature has noted, steel products are often reusable after the initial application[32] and, if not, the scrap metal is fully recyclable. In terms of recycling, steel is ideal because it does not suffer from the "down cycling" that is typical of other widely recycled materials, such as plastic or glass.[33] Down cycling means

Figure 1. A simplified example of the life cycle of a car hood plate.



that end products made from recycled material are inferior to those produced from fresh raw materials.

Our steel industry case highlights that, even if the material is ideal for recycling, there needs to be a purpose-built ecosystem working for recycling for the closed-loop economy to prosper. In addition to the long lifespan of steel, products that originated from a single slab of raw steel might end up in a myriad of different applications. Numerous actors handle these applications and combine them with various items to construct a final product that will be maintained, repaired (using spare parts) and finally discarded. Again, Pearlite offers an example of a plausible lifecycle for a steel product that serves as a hood plate in a car (Figure 1). Although the cycle is simplified, it proves that a series of production steps leads to a finished product and that the manufacturing phase comprises only a part of the total lifecycle. It is possible to produce the vehicle in several ways, but every step in the loop will probably relate to a different actor. In the traditional way of operation, a change in actor most likely will result in a loss of information because the next operator will not be able to track down any of the information generated in previous steps. If they ask the previous actor for details, the information gap will most likely be enormous given that a company cannot be certain where in a batch or production line a single plate delivered to the customer originated.

For the closed-loop business model to be sustainable in the long run, it needs to be self-reinforcing. This requirement can be met by generating virtuous cycles within the business model. Whereas policy makers may enable future material efficiency by requiring a greater release of data about the use of materials, managers need to accustom their organizations to taking full advantage of material intelligence. For instance, the development of materials for reuse from the outset emphasizes the need to manage the information concerning the material even before the material exists. The use of that information becomes more effective through feedback loops that make use of the domain expertise. Moreover, intelligence pertaining to the composition of a material and the contingencies of its uses makes an important keystone for the recyclability of things. Given the growing importance of information management on technological platforms, the development of a more comprehensive understanding of the promises and perils of information sharing is a fertile area deserving of further study.

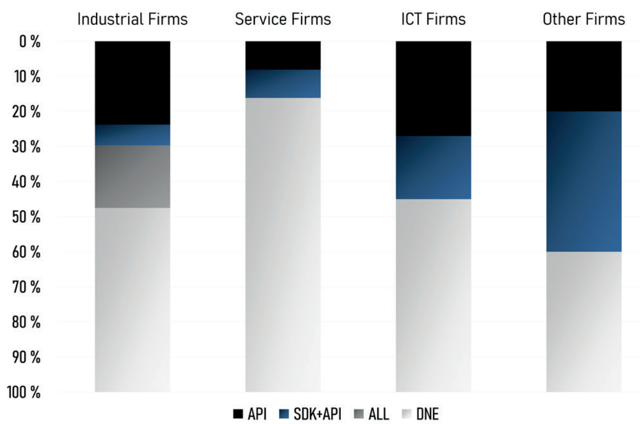
In conclusion, when evaluating the potential of a business model in a closed-loop ecosystem, it is important to note that mastering the learning process that leads to new information is more valuable than merely possessing information. Additional empirical and conceptual research is required to develop a more precise and nuanced understanding of closed-loop business models based on multi-actor platforms. In particular, managers need to comprehend the logic of their particular business ecosystem and develop the appropriate capabilities in their corporate networks to compete successfully.

Appendix 1: Firms' technical boundary resources for ecosystem connectivity

In November–December 2015, we examined firms' capabilities to participate and enable participation to their digital platforms and ecosystems though technological boundary resources. The data covers large and medium-sized firms in the technology industries, in the service sector, in information and communication technology (ICT) and in other industries.

Data for this analysis were gathered with Finnish Government project on digital platforms (see Ailisto *et al.*, 2016). Acronyms used in Figure 2: SDK – Software Development Kit (i.e., tools for software development provided by the company); API – Application Programming Interface (i.e., any defined inter-program interface provided by the company); Scripts (i.e., a program or sequence of instructions that is interpreted or carried out by another program, any complementary functionality); ALL – All of the above; DNE – Does not exist (that is, firms in the survey did not offer any of the three resources).

Figure 2. Firms' technical boundary resources for ecosystem connectivity across industries (N=45).



	INDUSTRIAL FIRMS	SERVICE FIRMS	ICT FIRMS	OTHER FIRMS
API	24 %	8 %	27 %	20 %
SDK	0 %	0 %	0 %	0 %
SCRIPTS	0 %	0 %	0 %	0 %
API + SDK	6 %	8 %	18 %	40 %
API + SCRIPT	0 %	0 %	0 %	0 %
SDK + SCRIPT	0 %	0 %	0 %	0 %
ALL	18 %	0 %	0 %	0 %
DNE	53 %	83 %	55 %	40 %

Appendix 2:
Qualitative data on firm-level activity in closed-loop ecosystems

Table 2. Informants and interviews.

COMPANY	INTERVIEWEE	DATE	DURATION
PEARLITE	Senior executive	March 2014	94 min
	Manager, Products	March 2014	53 min
	Senior executive	March 2014	82 min
	Vice president	March 2014	83 min
	Manager, Applications	March 2014	66 min
	Senior executive	March 2014	66 min
	Senior executive	March 2014	76 min
	Manager, Applications	March 2014	66 min
	Vice president	March 2014	56 min
	Senior executive	March 2014	92 min
	Senior executive	March 2014	65 min
	Manager, Construction	March 2014	40 min
	Manager, Product line	March 2014	73 min
	Senior executive	March 2014	111 min
	Manager, Applications	March 2014	111 min
	Manager, R&D	December 2014	31 min
	Manager, Production	December 2014	151 min
	Head of R&D	January 2015	54 min
	Manager, Services	February 2015	50 min
	Director, Services	February 2015	50 min
FIRM A	Software technology manager	April 2014	58 min
FIRM B	Accounts manager	April 2014	76 min
FIRM C	CEO	September 2014	29 min
FIRM D	CEO	September 2014	21 min
FIRM E	CEO	September 2014	30 min
FIRM F	CEO	September 2014	27 min
FIRM G	CEO	October 2014	27 min
FIRM H	CEO	October 2014	19 min
FIRM I	CEO	November 2014	27 min
FIRM J	CEO	November 2014	21 min
FIRM K	CTO	January 2015	80 min
FIRM L	Manager, Product development	February 2015	37 min
FIRM M	Manager, Systems	February 2015	53 min
FIRM N	Account manager, Materials	May 2015	95 min
FIRM O	Manager, R&D	December 2015	80 min
N=16	**Number of interviews: 35**		**Total: 35 h 50 min**

Table 3. Special interest group workshops held to review and validate findings.

TOPIC	KEY QUESTIONS	DATE
DIGITAL PLATFORMS ENABLING ADVANCED SERVICES	What is a digital platform? What are the opportunities and challenges?	January 27, 2017
REQUIREMENTS FOR PROVIDER OF DIGITAL SERVICES	What new capabilities and resources are required for success in digital services?	March 3, 2017
PREDICTIVE MAINTENANCE SERVICE OFFERING	How digitalization is supporting predictive maintenance?	April 19, 2017
VALUE-BASED SELLING, PRICING, AND BUSINESS MODELS	How digitalization is supporting value-based businesses?	May 11, 2017
FLEET-ENABLED SERVICES	What are the services that are only possible by fleet-level information?	June 8, 2017
SERVICE OFFERING AND PORTFOLIO MANAGEMENT	How can the service offering and portfolio be developed and managed efficiently?	August 22, 2017

Acknowledgment

The authors express their gratitude to the three anonymous reviewers and the editor for helpful comments that improved the paper. Also, the financial support to this research from BRIE-ETLA 2015–2018 and DIMECC Service Solutions for Fleet Management 2015–2017 research projects, funded by the Finnish Funding Agency for Innovation, is gratefully acknowledged.

Endnotes

1 For more information, see Kortmann & Piller, (2016). For the scope of this study, the term "*closed-loop system*" represents a subset of "*circular economy*," although the terms are often used interchangeably. A thorough analysis reveals some differences in how these concepts are used in the literature. An idealistic vision of a closed-loop ecosystem is what Boulding describes in his essay as the "spaceman economy." It portrays the world as having finite resources, where all new products must be comprised of existing or discarded ones. However, in reality, a more practical approach is what material scientists consider as the desirable goal for the circular economy. Julian Allwood frames such a perspective as: "rather than having circularity as a goal, a more pragmatic vision for a material future would be to aim to meet human needs while minimizing the environmental impact of doing so." We acknowledge the results of the recent literature review by Geissdoerfer, Savaget, Bocken and Hultink, (2017, p. 765), who define "the circular economy as a regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops". These targets may be achieved through the means of long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing and recycling. For more details, see for example: Allwood, (2014); Boulding, (1966); and Geissdoerfer *et al.* (2017).

2 Following Zott, Amit and Massa (2011), we define "business model" as a unique arrangement of firm's value-creating processes and the processes of value capture. In the context of our study, an important aspect of the business model of a firm is the way the processes of value creation and value capture are fitted to the processes of other actors operating in the same closed-loop system.

3 In 2015, we studied the drivers and effects of corporate sustainability in almost 100 Canadian companies, the majority of which operated in automotive vehicles manufacturing or electrical equipment, appliances and components manufacturing. We found that stakeholder pressures and management commitment boost the creation of closed-loop systems in terms of implementing zero waste manufacturing and green supply practices, and that the resulting advancements lead to novel skills, more innovative products, improved financial gains and environmental benefits.

4 The estimate emerged from our discussions with the Chief Metallurgist and Head of Research and Development at Outotec, Plc. in 2015. The use of copper originated in Asia, but 95-97% of all copper was mined in the past 115 years. For more information, see: http://www.copper.org/education/history/us-history/ (retrieved Feb 12, 2016).

5 In their recent research report, Seppälä *et al.* (2015) define "digital platforms" as "information technology frameworks upon which different actors—i.e., users, service providers and other stakeholders across organizational boundaries—can carry out value-adding activities in a multi-sided market environment governed by agreed boundary resources and objects. Typically, these actors create, offer and maintain products and services that are complementary to one another. Platforms quintessentially lure and lock in various types of actors with their direct and indirect network effects and economic benefits."

6 This perspective is in the heart of the "contingent resource-based theory," which investigates how the value of resources is contingent on the context and the linkages between primary and complementary resources. For more details, see, for example, Sedera *et al.* (2016).

7 Boulding's famous essay "The Economics of the Coming Spaceship Earth" has been considered as the cornerstone of circular economy discussion. In his essay, Boulding metaphorically describes economy through open and closed systems. He labels open economy, with a limitless supply of expendable resources, as the "cowboy economy" and, in turn, closed economy, without unlimited reservoirs of anything, as the "spaceship economy." (Boulding, 1966).

8 Suren Erkman describes the whole of materials and energy flows through an industrial system as "industrial metabolism." This concept connects closely to industrial ecology literature. Industrial ecology perspective considers industrial metabolism but includes an evolutionary view to unravel the technological trajectories within industrial systems. For more information, see Erkman (1997).

9 Ronald S. Burt introduced structural holes in his book *Structural Holes* (Burt, 1992). Building on his work, we define a structural hole as a gap between two individuals with complementary resources or information. In turn, a *tertius* is a third party positioned between two or more players, filling the gap between them. In formulating this definition, we acknowledge the work by Venkatraman, Lee & B. Iyer (2008).

10 An early twentieth-century sociologist Georg Simmel called such a third party as a *tertius gaudens*, a broker who profits or benefits from competition among two other actors. For more information, see Simmel (1902).

11 Burt examines this phenomenon through social capital that the structural holes can provide. See Burt (2004).

12 More accurately, this perspective on structural holes is the tertius gaudens variant of brokerage, where the focal actor upholds segregation. For more detailed analysis, see Obstfeld, (2005); Obstfeld, Borgatti & Davis (2014).

13 For more information, see bitvore.com (http://bitvore.com/2015/10/what-is-material-intelligence-and-other-faqs-part-ii/# (retrieved Jan 29, 2016).

14 For more information, see bitvore.com (http://bitvore.com/2015/10/what-is-material-intelligence-and-other-faqs-part-ii/# (retrieved Jan 29, 2016).

15 This definition for material intelligence agrees with prior approaches, which refer to the system-level benefits that accrue from the effective utilization of intelligent goods. For example, see Hakanen & Rajala (2018); Hakanen *et al.* (2017) .

16 Pearlite is a pseudonym.

17 In the platforms literature, on network effects, see *e.g.* Katz & Shapiro (1994); on multi-sided markets, see, *e.g.* Hagiu (2014); on complementary assets, see *e.g.* Teece (1986) and Dahlander & Wallin (2006); and on boundary resources, see *e.g.* Ghazawneh & Henfridsson (2013).

18 The efficiency of the processes and low cost of energy results in low cost of bulk materials, so that there is little if any economic incentive for recycling waste. Paper is a prime example; there is little motivation for either user or supplier to develop alternative material loops. For more details, see Allwood (2014).

19 Following Haigh *et al.* (2015), Rubicon's approach is a hybrid organization as their business model builds on "the alleviation of a particular social or environmental issue."

20 For more information about the Rubicon case, see: http://www.wired.com/2015/01/rubicon-global/. The business model of the venture is explained at http://rubiconglobal.com (retrieved Feb 3, 2016).

21 This claim has been put forward in many studies. See, for example, Santos & Block (2012).

22 Tesla's battery swap concept has some historical predecessors. For example, the Electric Carriage & Wagon Company operated a taxi service with a fleet of electric vehicles, where a central depot for quick battery swaps operated in Manhattan, New York in 1897 (Madrigal, 2011).

23 Technical boundary resources and objects reflect how companies ensure the interoperability of different goods such as software development kits (SDK), advanced programming interfaces (API) and readymade programming scripts for enhanced functionality of different applications and services (for introduction of technical boundary resources see Ghazawneh & Henfridsson (2013).

24 For a broader discussion about data ownership issues, see Ailisto *et al.* (2015).

25 Richard Scott uses a similar approach to distinguishing among different forms of organizing. For more information, see Scott & Davis (2015).

26 These categorizations include works by Gawer (2014); Gawer & Cusumano (2014); and Thomas, Autio & Gann (2014).

27 In their literature review of platforms, Thomas, Autio and Gann (2014) define leverage as "a process of generating an impact that is disproportionately larger than the input required." They identify three types of architectural leverage in platforms: production, innovation and transaction logic. One

of these logics dominates in a single platform, except in platform ecosystems that equally combine all three logics.

28 As stated by Gawer and Cusumano, (2014), the network effects can be either direct (more users connected to Facebook extends your community) or indirect (more Facebook users equal to more appealing media for advertisers). In both cases, the benefits grow at a drastic pace until reaching a point of saturation.

29 In the blockchain conference (in San Francisco, USA, Feb 10, 2016), John Wolpert, Director of products, IBM blockchain, underscores that the distributed ledger technology will soon replace the API economy.

30 Ownership can also entail the right to exclude others from accessing and using an asset. As the manufacturers' technical ability to commit products to specified behaviors, such as recycling protocols, becomes more pervasive, the owners' ability to exclude others from controlling their assets may change. As a practical example, the digital rights management (DRM) technologies employed by the media industry have already affected the de facto rights of ownership in certain types of immaterial property.

31 For similar reasoning, see Allwood *et al.* (2012).

32 Extending the products' lifecycle by reusing good-conditioned items provides possibility to reduce CO_2 emissions. For more information, see Fujita & Iwata, (2008); Ness *et al.* (2015); and Pongiglione & Valderini (2014).

33 See Chapter 23 in Callister & Rethwisch (2007).

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Article 2

Blockchain-Based Deployment of Product-Centric Information Systems

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Original publication:

Mattila *et al.* (2021). Blockchain-Based Deployment of Product-Centric Information Systems. Computers in Industry, Vol. 125(2), 103342.

Abstract

Collecting and utilizing product life-cycle data is both difficult and expensive for products that move between different industrial settings at various points of the product life-cycle. Product-centric approaches that present effective solutions in tightly integrated environments have been problematic to deploy across multiple industries and over longer timespans. Addressing deployment costs, incentives, and governance, this paper explores a blockchain-based approach for the deployment of product-centric information systems. Through explorative design science and systematic combining, the deployment of a permissionless blockchain system for collecting product life-cycle data is conceptualized, demonstrated, and evaluated by experts. The purpose of the blockchain-based solution is to manage product data interactions, to maintain an accurate single state of product information, and to provide an economic incentive structure for the provision and the deployment of the solution. The evaluation by knowledgeable researchers and practitioners identifies the aspects limiting blockchain-based deployment of solutions in the current industrial landscape. Combining theory and practice, the paper lays the foundation for a blockchain-based approach to product information management, placing design priority on inter-industrial and self-sustained deployment.

Keywords

product-centric information management, blockchain, inter-industrial deployment, platform sustainability

1 Introduction

Products in use—especially durable and capital goods—are valuable sources of information in many industrial settings (Aitken, Childerhouse, & Towill, 2003; Anderson & Zeithaml, 1984; Kärkkäinen, Holmström, Främling, & Artto, 2003; Rink & Swan, 1979). However, in settings where products move between systems and industrial settings at different points in the lifecycle, product data is rarely effectively collected and used (Lehtonen, Ala-Risku, & Holmström, 2012). Moreover, a combination of information asymmetries and a lack of incentives may even result in supply chain actors destroying data valuable to one another (Ala-risku, 2009).

The concept of *product-centric information management* (Kärkkäinen, Ala-Risku, & Främling, 2003; Meyer, Främling, & Holmström, 2009; Tang & Qian, 2008) was developed to enable multiple actors to share information on product individuals comprehensively over their lifecycle. While significant improvements have been observed in case studies (Bussmann & Sieverding, 2001; Främling, Holmström, Loukkola, Nyman, & Kaustell, 2013; Hribernik, Rabe, Schumacher, & Thoben, 2006; Lyly-Yrjänäinen, Holmström, Johansson, & Suomala, 2016; Rönkkö, Kärkkäinen, & Holmström, 2007), the deployment of product-centric information management as a sustained solution has been challenging. Deployment challenges include, *e.g.* high initial costs, scalability (Leitão, 2009; Tähtinen, 2018; Trentesaux, 2009), and unresolved conflicts of interest regarding platform control and governance (K. Främling, Harrison, Brusey, & Petrow, 2007). Establishing more integrated platform solutions for product data management has been similarly challenging (Naphade, Banavar, Harrison, Paraszczak, & Morris, 2011).

This conceptual paper explores blockchain-based deployment of a product-centric information system. The focus is on the use of blockchain-based functionality (Buterin, 2013; Hukkinen, Mattila, Smolander, Seppälä, & Goodden, 2019; Nakamoto, 2008; Poon & Buterin, 2017; Wood, 2013), such as protocols, crypto-mining payments, and smart contracts to initiate and sustain product data collection and use. The purpose is to conceptualize and demonstrate a solution, where the design priority is on the incentivization of actors to participate in providing item-level product lifecycle information, and reimbursing their efforts by using blockchain technology. This paper contributes to research on viable inter-industrial deployment (Alam & El Saddik, 2017; Naphade *et al.*, 2011) and self-sustained platforms (Blossey, Eisenhardt, & Hahn, 2019; De Filippi & Loveluck, 2016; Mattila & Seppälä, 2018).

2 Literature review

Storing and maintaining data on each product individual over its entire life cycle is not a trivial undertaking. The high initial investment has been identified as a reason for why integrated product data management systems have not been widely adopted by the industry (Leitão, 2009; Trentesaux, 2009). As an alternative, more loosely coupled peer-to-peer solutions have been proposed to share the burden (Främling, Kubler, & Buda, 2014; Kärkkäinen, Holmström, *et al.*, 2003; Kubler, Främling, & Derigent, 2015). However, while the use of a peer-to-peer approach reduces the investment cost of individual actors, it introduces a variety of new challenges for product centric information management, *e.g.* tracking and coordinating the global state of the system, attracting a critical mass of users, as well as facilitating authentication and trust in a decentralized manner (Petkovic & Jonker, 2007; Trentesaux, 2009).

2.1 Product-centric information and blockchain

In the field of product lifecycle management, earlier efforts towards using a peer-to-peer network have mainly been aimed at increasing the interoperability and openness of product data systems (Kubler *et al.*, 2017; Raggert, 2015). However, obtaining guarantees of the satisfactory performance of peer-to-peer networks has been found difficult; Due to the coordination constraints involved, evaluating the global state of a fully decentralized system—and thus predicting its behaviour—can be highly challenging (Trentesaux, 2009). Over the last decade or so, blockchain technology has provided a potential solution to this issue by enabling a single programmatic state to be maintained in peer-to-peer networks in an entirely decentralized fashion (Buterin, 2013; Hukkinen *et al.*, 2019; Poon & Buterin, 2017; Wood, 2013).

Consequently, in recent research literature, several conceptualizations have been drafted for using blockchain-related systems to improve the transparency and traceability (Azzi, Chamoun, & Sokhn, 2019; Caro, Ali, Vecchio, & Giaffreda, 2018; Cole, Stevenson, & Aitken, 2018; ElMessiry & Elmessiry, 2018; Galvez & Mejuto, 2018; Heber, 2017; Heber & Groll, 2018; H. M. Kim & Laskowski, 2018; Kshetri, 2018; Lu & Xu, 2017; Tian, 2016; Westerkamp, Victor, & Axel, 2018; Wu, Li, King, Miled, & Tazelaar, 2017), the sustainability (Bai & Sarkis, 2020; Kouhizadeh & Sarkis, 2018; Nayak & Dhaigude, 2019; Saberi, Kouhizadeh, Sarkis, & Shen, 2019), the cybersecurity and resilience (Banerjee, Lee, & Choo, 2018; Kshetri, 2017; Min, 2019; Papakostas, Newell, & Hargaden, 2019), and the integration and interoperability (Dai, Zheng, & Zhang, 2019; Gordon & Catalini, 2018; Huang, Wang, Yan, & Fang, 2020; Korpela, Hallikas, & Dahlberg, 2017; Miller, 2018; Repository, 2016; Ruta, Scioscia, Ieva, Capurso, & Sciascio, 2017) of supply chain and product data management structures. Some conceptualizations have also been presented specifically for distributed workflow management with blockchain-based smart contracts (Bahga & Madisetti, 2016; Chen *et al.*, 2017; Evermann & Kim, 2019; Leiding, Memarmoshrefi, & Hogrefe, 2016; Leng, Jiang, Liu, Chen, & Liu, 2017; Yu *et al.*, 2018). Furthermore, other closely resembling themes have been touched upon in many adjacent research streams, *e.g.* focusing on the use of blockchain systems for data governance (Liang *et al.*, 2017; Turk & Klinc, 2017) and ownership management (Karafiloski, 2017; Toyoda, Mathiopoulos, Sasase, & Ohtsuki, 2017; Zhang & Wen, 2017).

Despite the vibrant streams of publications on the issue in recent years, little attention has been paid to the challenge of combining solution deployment and sustainability at the inter-industry level. For example, (Elmessiry, Elmessiry, & Elmessiry, n.d.; Lu *et al.*, 2019; Sternberg, Hofmann, & Roeck, 2020) address the problem of successfully deploying a blockchain architecture for increased transparency and trust in inter-organizational supply chains but do not consider inter-industrial, or system-of-systems, integration. Conversely, (Jiang, Fang, & Wang, 2019; Özyılmaz & Yurdakul, 2019; Tijan, Aksentijevi, & Ivani, 2019) discuss using a blockchain-based architecture for creating an inter-industrial backend for the Internet of Things, but do not address the feasibility of solution deployment. (Katuwal, Pandey, Hennessey, & Lamichhane, 2018), on the other hand, briefly acknowledges the potential suitability of using a blockchain system as an incentivization mechanism to deploy a global health information exchange but does not address the solution sustainability aspect. Respectively, (Rajala, Hakanen, Mattila, Seppälä, & Westerlund, 2018) points out the need for self-reinforcing business models for sustainable systems-of-systems, but does not discuss the feasibility of solution deployment.

While potentially sharing a common manufacturing supply chain, product items do not usually follow one uniform chain of ownership throughout their individual lifecycles. Therefore, an inter-industrial perspective combining both effective deployment and self-sustainability is required in order to establish a prominent product-centric information solution, enabling transformational insight into individual product behaviour across national and industrial boundaries.

2.2 Blockchain systems and smart contracts

Blockchain technology is often described as a combination of information technology elements and methods enabling the creation of decentralized, distributed, and replicated digital ledgers. To this end, the technology employs *e.g.* peer-to-peer networking, public-key cryptography, digital tokens, multi-version concurrency control, and a cryptographically concatenated chain of data blocks used to store database modifications (Nakamoto, 2008).

For this paper, we define blockchain systems strictly as 1) open source and open access technology compositions; 2) comprising a non-hierarchical peer-to-peer networks without single points of failure or control; 3) which maintain consensus over cryptographically concatenated, shared and replicated append-only data structures; 4) according to deterministic self-contained consensus algorithms, void of external inputs such as validation by central authorities or off-chain signalling (Slootweg, 2016). In other words, we make a clear distinction between blockchain systems and the more loosely defined concept of distributed ledgers. A strict delineation of this kind is necessary, as the latter do not exhibit the same kinds of properties essential to solution deployment, as will be discussed later in this paper in Section 4.3.2.

In a computational sense, blockchain systems can be characterized as distributed state machines: peer-to-peer networks capable of maintaining a single programmatic state—or consensus—across the entire network and its shared data, without any single participant having authority over another. By employing Turing-complete programming languages, state-changing programs known as smart contracts can be created, stored and executed in the blockchain network to facilitate diverse distributed workflows (Buterin, 2013; "Ethereum Frontier Guide," n.d.; Hukkinen *et al.*, 2019; Poon & Buterin, 2017; Wood, 2013).

Smart contracts can be described as programmatic containers for tokenized assets. Essentially, they are persistent computer programs which have the ability to autonomously govern assets and to execute transactions. Once assets are deposited into a smart contract's address, they cannot be recuperated until the programming logic of the smart contract permits it. The logic of the smart contract itself is protected by the distributed blockchain network: any unauthorized attempt to tamper with its design is obvious, and easily discarded by other participants (Buterin, 2013; "Ethereum Frontier Guide," n.d.; Hukkinen *et al.*, 2019; Poon & Buterin, 2017; Wood, 2013).

By default, the execution environment of blockchain-based smart contracts lifeless. In order to interact with the smart contract's workflow in a state-changing manner, one must compensate the network on a per-operational basis for providing service. These compensations are also used to allocate request priority and to deter aberrant behaviour, such as requesting infinite computational loops. As each network interaction is bundled with its respective payment in this manner, any state-changing activities, such as database writes, are commonly referred to as 'transactions' in the blockchain vernacular ("Ethereum Frontier Guide," n.d.).

For this paper, we define smart contracts as digital computer programs that: 1) are written in computer code and formulated using programming languages; 2) are stored, executed and enforced by a distributed and replicated blockchain network; 3) can receive, store, and transfer digital assets of value; and 4) can execute with varying outcomes according to their specified internal logic (Lauslahti, Mattila, Hukkinen, & Seppälä, 2018).

2.3 Problem summary

Deploying product-centric information management systems over the product life-cycle is cumbersome, regardless of the technical approach, as all parties involved in the product-life-cycle also need to participate in the information management solution. Attaining a critical mass for a digital platform often requires considerable initial investments. To deploy a solution, the participation of at least one market side must be first subsidized to attract other market sides onto the platform *via* indirect network effects (Armstrong, 2006; Caillaud & Jullien, 2003; Hagiu, 2014; Hagiu & Wright, 2015; Katz & Shapiro, 1994). Consequently, in order to compensate the high-risk venture of establishing a solution in the first place, the pricing models often involve significant economic rent, reducing the appeal of participation (Gawer, 2009; Hagiu, 2014; Tähtinen, 2018).

Thus, understandably, the question of control and ownership of a product-centric information system has been at the centre of attention in research and development (K. Främling *et al.*, 2007). Recently, however, the problem of control and ownership has increasingly become reframed as a broader question of viable inter-industry deployment, especially in the research domain of cyber-physical systems (Alam & El Saddik, 2017; Naphade *et al.*, 2011; Porter & Heppelmann, 2014).

In addition to the problems related to deployment, another set of problems arises from the complexity of dynamic multi-industrial environments. The problem with static workflow designs is that in today's economy, supply chain structures are often complex and prone to reconfigurations (Ali-Yrkkö, Mattila, & Seppälä, 2017; Rajala *et al.*, 2018). While at the industry level, the data integrations and the required reconfigurations may be manageable, at the inter-industrial level the complexity in this regard increases exponentially. Therefore, even if all the parties involved were fully motivated to co-operate to their best ability, product data regarding individual product items could still become fragmented due to the information asymmetries involved.

The third problematic dimension is related to the motivation to preserve the product data workflow. So far, neither centralized nor peer-to-peer-based solutions have been able to provide a satisfactory solution to the problem of adequately incentivizing solution sustainability beyond individual commercial interests. While centralized models have suffered from asymmetrical power structures and single-points of failure, peer-to-peer models so far have lacked proper governance models to foster sufficient network effects for the solution to perpetuate (Ahluwalia, 2016).

3 Methodology

The proposal for an improved design presented in this paper was developed and evaluated by using an explorative design science research approach. Design science is a research method well suited for situations where a practical problem and its solution can effectively be examined through the development of a design artefact, such as a computer program, a system model, or a conceptual practice (Holmström, Ketokivi, & Hameri, 2009; Peffers, Tuunanen, Rothenberger, & Chatterjee, 2008). The design science approach was selected because it enables a rigorous way of designing, building, and evaluating a conceptualization for a product-centric information management system.

The study also incorporates elements of the methodology of systematic combining where an emergent theoretical framework, the empirical fieldwork, practical demonstration, and outcome evaluation are developed in a simultaneous, iterative process (Dubois & Gadde, 2002, 2014). While systematic combining is particularly useful for proposing new approaches and ideas for conceptual research, the main focus of this study is in new practice design. It assumes an integrational approach, providing a cross-disciplinary evaluation of the applicability of blockchain technology to address the challenges of introducing product-centric information management in an inter-industrial setting.

A former case study is also exploited and modified to demonstrate some of the key aspects of the conceptualized design proposal (Eisenhardt, 1989). The demonstration was iteratively developed and contextualized to a relevant product item example and industry setting. The programming of this design artifact draws from the methodologies of computer science (Ayash, 2014).

Through an evaluation procedure, design science enables research objectives to be addressed and problematic areas to be charted and pinpointed at an early phase, without waiting for large-scale implementation. To evaluate the validity of the de-

Table 1. A description of the evaluation interviews.

SUBJECT	1st ROUND DURATION	2nd ROUND DURATION	AGE	OCCUPATIONAL TITLE	AFFILIATION	EXPERIENCE IN PRODUCT DATA SYSTEMS (YEARS)	EXPERIENCE IN BLOCKCHAIN TECHNOLOGY (YEARS)
#1	51 min	45 min	39	chief technology officer	industry	11	4
#2	68 min	75 min	54	industrial internet facilitator	academic	25	4
#3	61 min	71 min	34	university lecturer	academic	8	0
#4	61 min	45 min	42	entrepreneur	business	20	4
#5	60 min	61 min	55	program manager	industry	25	0
#6	51 min	58 min	24	doctoral candidate	academic	5	2
#7	56 min	51 min	45	head of digitalization	regulator	0	4

sign proposal, and to provide further in-depth insights into the conceptualization, two rounds of seven qualitative interviews were conducted in a semi-structured manner. The interviews were not intended as a substitute for field testing of the design proposal, but for evaluating the key assumptions and concepts, as well as mapping the critical issues related to the implementability of the design. In other words, the aim was to involve the interviewees in exploring what aspects of the problem situation are important from the interviewee perspective, and how these concerns relate to their view and evaluation of the design proposal. A description of how the evaluation sessions were carried out is presented in Appendix A.

The interviewees were selected in an opportunistic fashion, based on their credentials and expertise, and their heuristically evaluated ability to provide the most valuable insights on the design proposal. The first round of evaluation interviews involved a generic system-level demonstration which was not contextualized to any particular product item or industrial setting. The follow-up interview round involved a more detailed and contextualized iteration of the design proposal with a specified product item, a conceptual data model of the product system architecture (not to be confused with a product data model), and an improved source code artefact with more elaborate incentivization and payment mechanisms. The follow-up interviews also involved a Delphi segment (Dalkey & Helmer, 1963) which allowed the interviewees to comment on the summarized key points from the first round of interviews and to readjust their views. The interview questions around which the interviews were framed is included in Appendix B.

4 Solution proposal and demonstration

4.1 Objectives for a solution

On the basis of the problem summary in Section 2.3, we determine that the main objective for a solution is a design for a product-centric information management system which can be deployed across many industries in terms of costs, coordination, and critical mass, and which can sustain its own existence independently. We postulate that in order to achieve such a design, the system should be able to satisfy the following conditions and specifications: Firstly, the design proposal should be able to a) *enable participation* of all the willing parties. In order to achieve this, the system should feature ahierarchical governance. Secondly, the proposal should be able to b) *prevent data and workflow fragmentation* in a dynamic environment. For this purpose, the system should be based on replicated and distributed architecture. Thirdly, the design proposal should be able to c) *ensure data and platform sustainability* over the complete lifespan of product individuals. For this reason, the system should involve an inherent incentivization mechanism.

4.2 Design principles

We address the research problem and our objectives for an improved design with an approach based on blockchain technology. The motivation for choosing this approach stems from the observation that permissionless open source blockchain systems exhibit a range of properties which conveniently line up with our objectives for a solution. Firstly, due to their ahierarchical governance structure, blockchain systems can be well-suited for enabling participation. Secondly, their blockchain data structure and consensus mechanism can be very effective in maintaining multi-version concurrency control in a decentralized fashion. And lastly, crypto-token-based incentivization mechanisms can be directly incorporated in their participation protocol. Furthermore, the chosen approach comes with a proven track record of several peer-to-peer networks already having been successfully deployed in the described manner in the past (*e.g.* Bitcoin, Ethereum).

In order to accomplish our objectives for a solution, the demonstration of the design proposal needs to show that blockchain systems can be used to involve new parties in the product data system. The demonstration also needs to demonstrate that blockchain systems can be used to include new information as a part of the product-centric information management system. Furthermore, the capability for facilitating adequate incentive structures also needs to be demonstrated.

In this paper, we demonstrate these abilities by employing a smart contract to facilitate a product individual's lifecycle journey. The smart contract was designed for Ethereum, as it represents a suitable deployment environment successfully established in a similar manner as conceptualized in this paper. The other option would have been to establish an entirely new blockchain network as a designated deployment environment for product-centric information management. While perhaps better suited for the actual purpose of the use case, this approach would be difficult to demonstrate in a similar capacity and therefore was not pursued in this paper.

In transitioning from product class data to product-centric information management on individual product items, the number of required transactions can be expected to increase many-fold. Furthermore, as individual product items journey through their individual product lifecycles and paths of ownership, the number of information sources and different data system interactions can also be expected to increase heavily. In order to ensure that the data regarding all the product individuals is provided by all the relevant parties, data provision should be directly rewarded at the level of the participation protocol. For seamless inter-industrial functionality, the system should be constructed so that data exchange can happen spontaneously. In other words, no premeditated *ad hoc* data system integrations should be required between the participants, other than with the blockchain network itself. To this end, the demonstration also illustrates how these incentivization mechanisms can be facilitated by a blockchain-based system design. Furthermore, we also conceptualize, how the provision and the development of the product-centric information system itself can be incentivized by a blockchain-based approach.

4.3 Demonstration of blockchain-based deployment: A loader crane for commercial vehicles

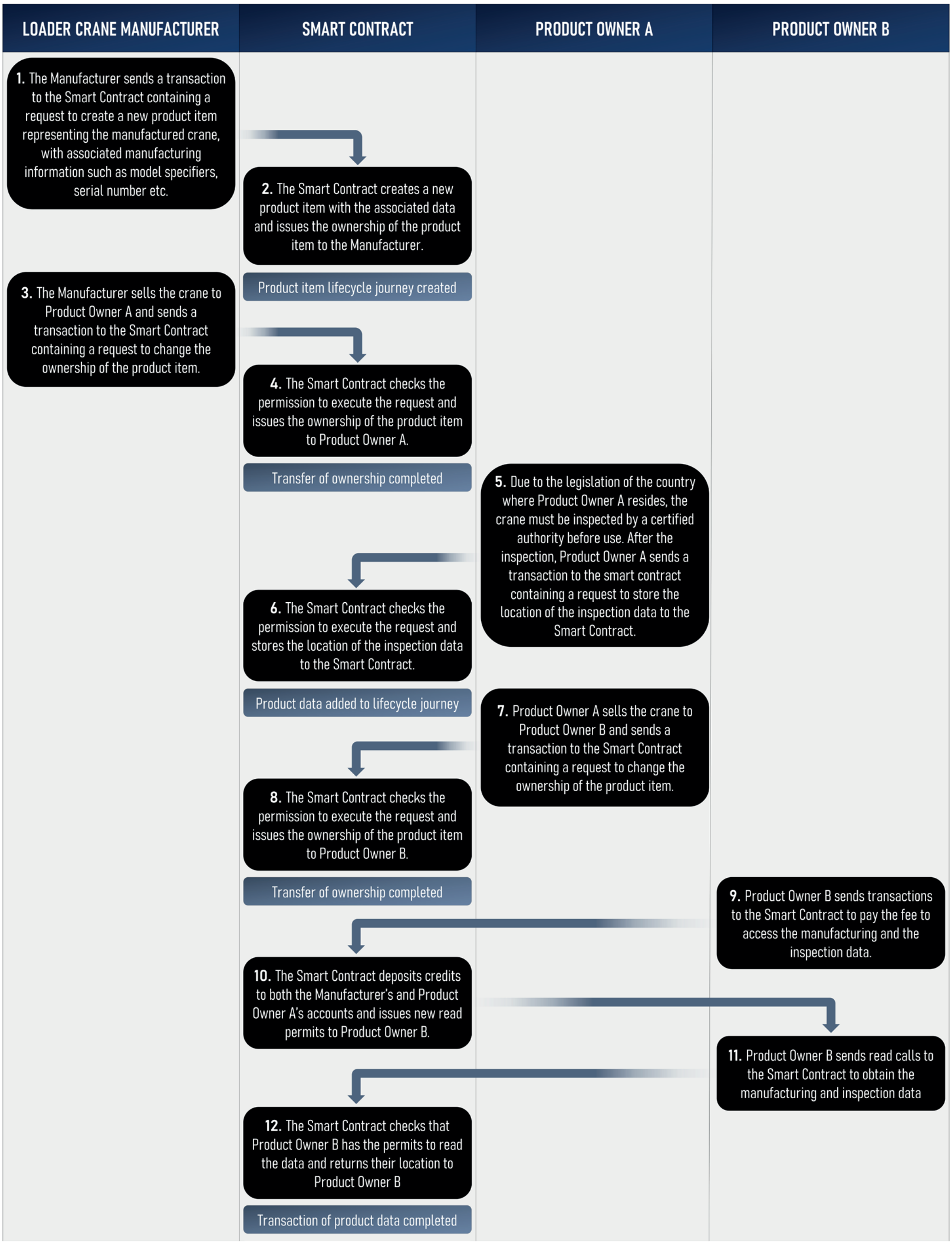
The demonstration of deployment concerns an illustrative product individual, a loader crane for commercial vehicles. These types of loader cranes are manufactured by companies such as Palfinger of Austria, and Hiab of Sweden. The loader crane is typically mounted on a new vehicle before delivery to the customer by the dealer. However, it may also be installed on a vehicle at a later time by the OEM of the loader crane. When the vehicle reaches the end of its life-cycle, the loader crane can be remounted to a different vehicle. This way, the life-cycle of the crane exceeds that of the vehicles to which it is mounted. Over its life-cycle, the loader has many different owners. Furthermore, not only can it be mounted to different vehicles, it can also be repurposed and refurbished by other organizations than the OEM. Product individual data on the loader crane needs to be collected in many countries due to safety regulations.

4.3.1 Participation protocol overview

To demonstrate the conceptualization drafted according to our specified design principles, we present an example protocol of a manufacturer deploying product-centric information management over the product life-cycle of a loader crane (see Figure 1). We demonstrate how the relevant contractual and incentive functionalities in each step are defined in the source code that forms the smart contract in Appendix A. The complete and functional source code for the demonstration can also be found at (Valkama, 2020).

The participation protocol of the demonstration begins with the reception of a new loader crane order by the manufacturer. At this stage, we assume that the smart contract facilitating the workflow for the product life-cycle journey is already deployed in the environment consisting of *e.g.* vehicle manufacturers, loader crane OEMs, truck dealers, trucking firms, and service and maintenance companies. In this conceptualized implementation, after the crane has been manufactured, the manufacturer sends a transaction to the smart contract, requesting that a new product item life cycle journey representing the physical crane is established in the blockchain and its ownership assigned to the manufacturer. In addition, the request contains manufacturing information such as crane model specifiers and a serial number to be stored on the product item (1).

Figure 1. Participation protocol for blockchain-based deployment of product-centric information management over the life-cycle of a loader crane.



After this step has been executed by the smart contract (2), the manufacturer can now control the product item in the product data system. As the current owner of the product item, it is possible for the manufacturer to store additional data to the lifecycle journey or query the data already stored without any extra fee.

Upon the sale of the crane to a vehicle manufacturer the crane manufacturer initiates a new transaction in the smart contract in order to transfer the ownership of the product item to the new owner (3). Consequently, the smart contract checks for the permission to perform the request and updates the lifecycle journey accordingly (4).

Over the life-cycle of the loader crane, a multitude of information relevant to different parties is accumulated and can be linked to the smart contract. In the example scenario, once the vehicle manufacturer receives the crane from the loader crane manufacturer, the crane is required to pass an individual inspection performed by a certified authority before it can be installed and used on a vehicle. After the inspection, the vehicle manufacturer sends a transaction to the smart contract in order to store the location pointing to the inspection data (5). Upon receiving the request, the smart contract ensures that the sender of the request is the current owner of the product item and then stores the datum to the smart contract (6).

Once the crane has been mounted onto a vehicle, the vehicle manufacturer delivers the assembly to a truck dealer to fulfil a pre-existing purchase order on the vehicle. Upon the delivery, the vehicle manufacturer sends a transaction to the smart contract in order to transfer the ownership of the product item to the truck dealer (7). The smart contract once again checks for the required permissions and then executes the transfer of the ownership (8).

Before putting the vehicle out for sale, the truck dealer must complete the vehicle registration process and provide documents to the registration authority which prove the vehicle's suitability for its intended use. In order to do this, the truck dealer requires all the relevant information regarding the vehicle's life-cycle journey. To obtain this information, the dealer first sends transactions to the smart contract to pay for the access to the manufacturing and the inspection data from the smart contract (9). Upon receiving the payment transactions, the smart contract deposits credits to the accounts of both the loader crane manufacturer and the vehicle manufacturer for the data they have contributed earlier. Subsequently, the smart contract grants the truck dealer access to the data (10). After the payment transactions have been successfully completed, the truck dealer sends queries to the smart contract to read the relevant data (11). Finally, the smart contract checks that the truck dealer has the valid access and returns the requested data (12). The truck dealer can now proceed with the registration of the vehicle.

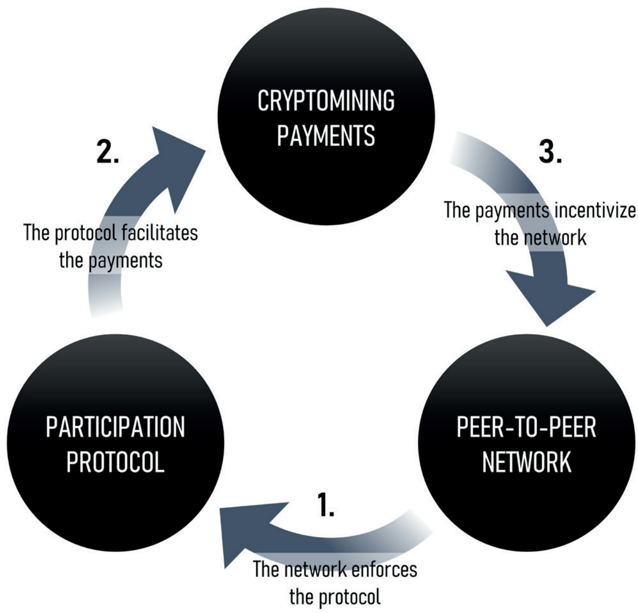
4.3.2 Incentivizing the provision of the product-centric information system

The successful deployment of an inter-industrial product-centric information system, such as the one outlined for the loader cranes, is intricately linked to the concept of *network effects*. In economics, a direct network effect occurs when the value to an agent from using a product, a service or a system depends on the extent of its use by other similar agents. Indirect network effects, in turn, occur when such an increase affects the users of a different product, service or system (Armstrong, 2006; Caillaud & Jullien, 2003; Katz & Shapiro, 1994).

Blockchain-based solutions incorporate a mechanism for a positive feedback loop of indirect network effects to incentivize solution deployment. In essence, the blockchain-based operations described in Appendix A begin by drafting a participation protocol—an elaborate set of rules of engagement to which the participants must adhere in order to be acknowledged by the peer-to-peer network. The actor who initially seeks to create the solution for loader cranes starts the deployment by formulating and publishing the participation protocol. Blockchain systems make use of this participation protocol by inherently embedding financial incentive structures for platform collaboration directly into the protocol itself.

The protocol is open, both allowing new actors to join, as well as the introduction of other types of products than loader cranes. Figure 2 illustrates the positive

Figure 2. The growth-fostering positive feedback loop of network effects in blockchain systems.



feedback loop of network effects in blockchain-based deployment. The blockchain system involves a set of rules to which all participants must adhere in order to be acknowledged as members of the network. By contributing computational work, as instructed by the rules of the system, the network enforces a single state of the participation protocol (1). The participation protocol handles each product individual's lifecycle journey and the interactions with it, including the payment transactions for providing product data (2). As each payment also includes a compensation to the network operators for providing service, this incentivization attracts more participants to provide data and to operate the network (3). As the network grows larger, contributing even more computational work (1), the participation protocol grows more robust, making the data and the respective payments in the system more valuable (2). This, again, strengthens the incentives to participate (3), and so on (Athey, Parashkevov, Sarukkai, & Xia, 2016; Athey & Roberts, 2001; Catalini & Gans, 2016; Mattila & Seppälä, 2018).

4.3.3 Incentivizing the provision of product data

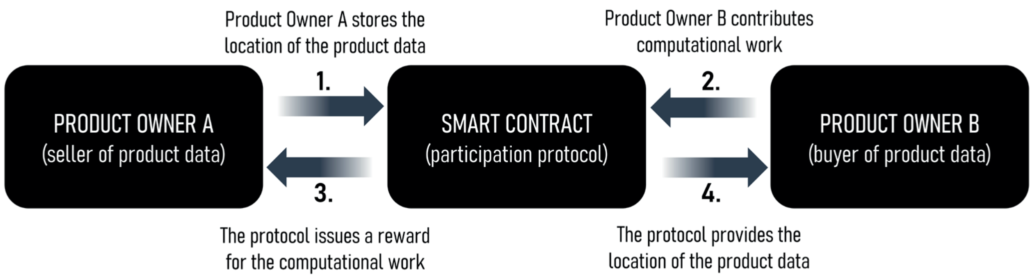
A product datum regarding an individual loader crane can be of very low value to the transacting participants in itself. Therefore, it can be difficult to facilitate the corresponding payments globally in a dynamic environment by any traditional means. Furthermore, in order to maintain the decentralized quality which makes the solution appealing to all parties, the payment processing should also be executed in the same decentralized manner.

While blockchain systems can be used for direct payment processing, they do not scale well in terms of transaction throughput capacity. Therefore, directly facilitating payment transactions through smart contract workflows can quickly become infeasible in large numbers (Hukkinen *et al.*, 2019). Blockchain systems do, however, enable an alternative microtransaction mechanism through the use of crypto-mining payments.

Crypto-mining payments are based on the fact that blockchain systems, require constant inputs of computational work to maintain their single state. Normally, providing this work entitles its contributors to rewards in the form of cryptographic tokens of value in order to incentivize participation. The rewarding is carried out *via* an inflationary tax on the entire network by issuing a small number of new tokens to the recipient of the reward, thus adding tokens into the token supply of the network and depreciating the value of each individual token in the process (Mattila & Seppälä, 2018).

In crypto-mining payments, the cost of the computational work contributed to the network and its respective reward are disentangled from one another to facilitate a payment transaction (see Figure 3). Once the seller has provided the item of

Figure 3. The mechanism of a crypto-mining transaction, as conceptualized in the participation protocol.



sale to the smart contract (1), the buyer contributes computational work to maintain the network's concurrency control, expending electricity which effectively constitutes the payment (2). The smart contract then allocates the respective mining reward issued by the network to the seller (3). Finally, the item of sale is delivered to the buyer (4). In essence, in crypto-mining payments, the act of making a payment always simultaneously contributes to the provision of the payment processing platform itself (Pearson, 2018; Rüth, Zimmermann, Wolsing, & Hohlfeld, 2018).

5 Evaluation

5.1 Technical design

The interviewees unanimously considered the loader crane a good product example and an appropriate industrial setting for the conceptualized design proposal. Two of the interviewees commented (#2,3), however, that while the conceptualization seems well-suited for the loader crane—*i.e.* a product of mid-range complexity—in reality product-centric information management must be extended to far simpler products and sub-components than the crane; In such cases, tracking the material and component identities and incentivizing collaboration could become more challenging *via* the conceptualized design, according to the two interviewees. Mostly the interviewees agreed (#1,4,5,6,7), however, that in a full implementation, the participation protocol could be expanded to facilitate the real-world complexity of a product individual's life-cycle.

The final iteration of the participation protocol was considered a sound design and logically coherent by all of the interviewees. One of the interviewees felt (#4), however, that a better possible way of configuring the participation protocol would have been to assign the loader crane product individual with its own unique identity in an equivalent manner to the manufacturer and the owners, and to use the smart contract's workflow only as a transaction link layer for the identities, the data, and the associated payments: "*This, I think, would have been more in line with the current Industry 4.0 digital twin mentality. The added benefit here would be that this participation protocol could guarantee the identities of the agents and product individuals when interacting through this kind of a link layer.*"

As a noteworthy point for further development, one of the interviewees also remarked (#7) on the design proposal's low threshold for extensive field testing: "*One good thing about this conceptualization is that it wouldn't be a huge effort to try this in practice. It's a classic example of a problem that is so complex that it's difficult to anticipate what would happen, so the easiest way to find out would be to simply try it out. And since the concept itself mainly deals with metadata, the risks for the participants would also be quite low.*"

5.2 Enabling participation

In Section 4.1, we postulated that in order to achieve our design objectives, the design proposal should feature ahierarchical governance to enable full participation by all the willing parties. To reflect this design principle, the solution proposal was based on a peer-to-peer blockchain architecture with no centralized authority or any designated individual or group responsible for the solution provision.

The distributed design approach was considered a good and sensible starting point for enabling open participation by all interviewees. Interviewees mostly agreed (#1,4,5,6,7) that successfully establishing an inter-industrial infrastructure at scale will require some new type of an approach. While a caveat offered (#1,6) that starting in the right place does not necessarily mean arriving at a functional solution, the proposed design was generally seen (#1,4,5,6) as a step in the right direction in the design principles. As described by interviewee #4: "*If we think about the loader crane industry, this kind of a systemic approach and the entire platform-building way of thinking is still quite alien to them. However, I think this is the only way to enable vast collaboration between different agents around a single product individual's lifecycle. I don't think any other approach would work at such a high level of scope.*"

The interviewees also largely agreed (#1,4,5,6,7) that the conceptualized open source, open access, and blockchain-based deployment would significantly reduce the costs of solution deployment and lower the barriers of entry into the product data market. The interviewees mostly agreed (#1,4,5,6,7) that the open access design and the role flexibility in solution provision should make participation more inviting, as its less constrictive nature means that participants are free to pursue business opportunities without restrictions by the solution provider. For inter-industrial deployment, this prospect was also considered pivotal (#1,4,6,7) because of the excessive difficulty of any solution provider anticipating all the use cases and business models in which potential participants are interested in an inter-industrial setting. However, arguments were also made (#1,4,6,7) that certain functions could still end up requiring centralized services to be offered on top of the system, involving additional fees for the users; For example, the identities of the users and the product items could turn out difficult to onboard in a completely decentralized fashion.

While the open access to become a provider for the solution architecture was also considered (#2,3,4,6) beneficial for the trustworthiness of the system, one interviewee had (#7) reservations in this regard: ”*With this kind of deployment, the network could end up being operated by parties not really involved in the supply chain structures at all. Of course, then you are faced with administrative questions, such as can these parties be trusted and is it really sensible that just literally anyone can start operating the data network. Or do we, after all, want to retain a little bit more control in the hands of those who actually use the data and the system?*”

Some concerns were also raised regarding the scalability of the conceptualized design. These concerns were mainly related to three key points. The first point of concern mentioned (#1,2,5,6) by the interviewees was the possibility of runaway costs due to system inefficiencies as the system is scaled up. This consideration stemmed from the technical properties of the conceptualized solution architecture (*e.g.* the requirement of constant inputs of computational work).

Another point of concern brought up (#1,5,6) regarding scalability had to do with the practical difficulty which often arises in the finer details of scaling up proofs-of-concept and other conceptual solutions. Building conventional IT solutions is a safer practice with a lot more history and experience on avoiding the potential pitfalls. A novel permissionless blockchain-based approach at scale is likely to produce a variety of unforeseeable problems and security issues, such as uncharted attack vectors, which need not have been considered in more traditional approaches.

Lastly, the third scalability-related point of concern mentioned by one interviewee (#2) was the presence of “walled gardens”—the purposeful lack of interoperability maintained by some industry actors as their competitive strategy. Some interviewees felt (#4,6), however, that this kind of a mindset was becoming less common and would be phased out by the market within the next 5–10 years; While customers have not been willing to pay extra for smart product features, market competition is making the smart product approach increasingly a necessity in maintaining a competitive product.

5.3 Preventing data and workflow fragmentation

As our second design objective we stipulated that the system should be based on replicated and distributed architecture in order to prevent data and workflow fragmentation in a dynamic network.

Contemporary solutions to product information management have often involved building case-specific *ad hoc* integrations between the data systems of the vendor and the client. Many of the interviewees expressed (#3,4,5,6) the opinion that due to the difficulty of indexing such *ad hoc* solutions in current configurations, the conceptualized design proposal could help locate the source of product data with greater ease. As explained by interviewee #6: "*When a new system comes along, an integration is built to each pre-existing system. And so the number of APIs absolutely skyrockets, and the system doesn't scale. And at the end of it all, the PLM people are left wondering where the master data is coming from, which systems are integrated with what, and so on. This conceptualization could provide a standard way of transferring the product data between all the various systems.*"

The conceptualized design proposal was purposefully left agnostic in terms of the product data format and meta data standards. The interviewees largely considered (#1,2,3,4,6) this a valid decision, pointing out that specifying a universal standard suitable for the needs of all actors in a cross-industrial context would be exceedingly difficult.

Defining machine-readable formats and relevant meta data standards was, however, considered (#1,2,4,5,6) one of the most important aspects for any shared inter-industrial or even intra-industrial use to be possible. For example, as pointed out by one of the interviewees (#1): "*You want the information fields to have enough flexibility to be able to cover anything, like a potential repurposing of the product, but at the same time, you need enough rigidity to pick up the elements that are important for the loader crane. You need to have the different loader crane manufacturers input similar data in comparable form. That structure is really important.*"

Some the interviewees elaborated (#1,3,4,5,7) that determining such data ontologies was a task best left for the markets and the soft law efforts of each specific industry. As expressed by interviewee #3: "*At the end of the day, everything hinges on what kinds of product data models are demanded by the customers. This way, companies could be forced to switch over to using different kinds of models.*"

In the demonstration's participation protocol, the product data is not stored in the blockchain, as such an approach would hardly be technically feasible. This aspect aroused both positive and negative considerations. The most obvious concern was the fact that the product data still needs to be stored somewhere. While the conceptualization does not describe in detail how the product data could be stored, the interviewees were (#1,4,6,7) open to the exploration of InterPlanetary File System -style solutions. InterPlanetary File System (IPFS) is an open-access peer-to-peer network designed to store data by using content-based addressing. In other words, a given address always points to the same content, thereby preventing data fragmentation within the network[1].

As a positive side, not storing the product data into the blockchain database was seen (#2,4) to enable further access control by each data provider at their end as they see fit. One noteworthy possibility enabled by this aspect, as pointed out (#4) by one of the interviewees, would be the facilitation of product-centric data products. Differing from data-driven applications, such as software solutions using API-based data for analytics, data products are independent, self-adapting entities which combine data inputs with analytical tools and models to produce new outputs of broadly applicable refined data (J. Kim & Bengfort, 2016). Currently, the API-driven solutions utilized in contemporary approaches are insufficient to construct and manage data products effectively. The conceptualized design proposal could offer a way to record and track the product and user identities, ownership relations, and the relevant data ontologies in a more constructive manner.

5.4 Ensuring data and solution sustainability

As the third objective in our design approach, we stated that the system should include an incentivization structure in order to ensure data and solution sustainability over the complete lifespan of product individuals.

One potential problem in this aspect which was pointed out (#1,3,7) is that designing universal incentive structures can be overwhelmingly difficult. For example, if actors were directly compensated for performing transactions of data into product items' life cycle journey, this could lead to the said actors purposefully bloating the system. Similarly, if a generic part of lesser quality is used in maintenance, adding this information to the product data could reduce the resale value of the product. Therefore, the owner may not be inclined to do so, regardless of the incentives embedded in the participation protocol.

While many of the interviewees felt (#2,3,7) that the problems stemming from humans cutting corners cannot be mitigated by incentives embedded in the participation protocol, the resulting market mechanism could alleviate the problem, as explained (#1) by one interviewee: "*If there are 100 fields which should be inputted for the loader crane, is there an incentive to update the fields that are the most popular and have the most valuable use cases? When the system has the incentive mechanism you have conceptualized, I think it will happen organically. When you leave it to a market mechanism, the market will find out which data is more valuable.*"

Another point raised (#2,3,4,6,7) by many of the interviewees regarding the participation protocol was that the system cannot necessarily be perpetuated with internal token incentives alone. Some external motivation for preserving the product data is required outside of the system itself. The interviewees estimated (#1,4,5,6) that the stakeholders in the loader crane's lifecycle would be willing to pay in the order of magnitude of tens to hundreds of euros for relevant data on their product items to be made available upon request, depending on the specific circumstances. This was seen to be motivated by *e.g.* opportunities of increased sales and modernization, regulatory compliance, and reverse logistics at the end of the product lifecycle. Heuristically, the amounts were considered (#1,4,5,6) sufficient to enable the sustained facilitation of the curated workflow, as proposed by the design.

The crypto-mining payments conceptualized in the design proposal provoked a mixed reception. On the one hand, the idea was widely considered intriguing. The notion that every payment transaction also simultaneously contributes to the provision of the underlying payment processing architecture was largely seen (#1,2,4,5,6) as an interesting prospect for fostering positive network effects and producing a positive scaling effect for the deployment of the network. Also, the implications for machine-to-machine payments and the idea that smart devices equipped with some CPU capacity and an internet connection could autonomously pay other devices directly for the curation of their own product data throughout their lifecycles mostly aroused (#2,3,4,5,6) interest.

On the other hand, a majority of the interviewees was concerned (#1,4,6,7) that implementing such a payment model would create an extra layer of unnecessary complexity and token price stability issues, potentially requiring some kind of a middleman to mitigate. Also, in regard to the prospect of M2M payments, it was pointed out (#1,2,3,6) that currently, the vast majority of industrial internet devices in use do not have the required smart capacity to carry out such payments. In the words of interviewee #6: "*Usually the software in products like loader cranes is quite specialized and proprietary, so I imagine adding the capability for crypto-mining payments would be quite a painful endeavour in a larger scale.*"

Due to these considerations, mostly the interviewees largely agreed (#2,3,4,6,7) that while an interesting prospect in its own right, crypto-mining payments would not be feasible as the only possible payment option in the present configuration of industrial systems.

6 Discussion

Several limitations apply which should be acknowledged when interpreting this exploratory study and its findings. Firstly, this study did not explore the integration of the demonstrated design proposal with other IT systems. Secondly, the study did not consider the details of viable product data formats in product-centric information management or the heterogeneity of real-world product data in general. Thirdly, the study did not address the question of how the actor and product identities could be onboarded in a fully decentralized fashion.

The applied semi-structured interview approach is limited in comparison to the more extensive field testing needed for empirical findings and design iterations in accordance with the design science process. The purpose of the loader crane demonstration and its evaluation was not to capture the complexity of a real product lifecycle, however, but to illustrate how a blockchain-based deployment of a product-centric solution could be configured to facilitate the necessary core functionalities for handling the product data, the agent identities, and the incentivization mechanisms required for a full scale implementation. Aiming at a solution that can be deployed across different environments over a long period of time, we seek to contribute to the research on viable inter-industrial deployment (Alam & El Saddik, 2017; Naphade *et al.*, 2011) and self-sustained platforms (Blossey *et al.*, 2019; De Filippi & Loveluck, 2016; Mattila & Seppälä, 2018).

While the use of a blockchain-based system offers a different set of abilities than more conventional approaches, some general problematic aspects regarding its utilization remain which were also not addressed in this paper. For example, while the participation protocol can algorithmically manage the solution provision and the product data workflow, the governance of more strategic development goals remains an open question in the research of blockchain systems (Mattila & Seppälä, 2018). Also, some criticism has also been presented regarding the alleged decentralized nature of blockchain systems in the first place (Walch, 2019).

The proposed approach enables anyone to freely enter the system in any market role and to produce open innovations for all areas and functions of the system. This approach, we anticipate, would create power dynamics where all participants are—not necessarily *de facto* equally powerful—but at least algorithmically equipotent and equally privileged by default. In such a system configuration, no participant would have an obligation to participate in the development, provision, or financing of the system architecture and its auxiliary services, but respectively, no participatory role or function would be off-limits to any participant willing to engage in its provision.

The proposed design presented in this paper extends product data management beyond standard systems. In our proposed design, many such systems are linked in a controlled way, with the product individual as the focal and organizing entity. Even when different actors use their own solutions for product life cycle management information, this information is purposefully collected and distributed between these many systems and actors. Our proposed solution makes it possible to incentivize the collection and distribution of high-quality and high-value product lifecycle information for many different types of product data residing in different systems. This is achieved through a mechanism for different entities to initiate and reward this controlled linking. For example, for a composite product with different modules, the product design and manufacturing information is located in the different PLM systems of the OEMs (*e.g.* Windchill, Teamcenter). The asset and performance data is located in the current and previous owners' operational systems (*e.g.* IBM Maximo, Avantis EAM), and service delivery in the systems of different service providers maintaining and supporting the systems (*e.g.* SAP, Odoo). With the proposed solution, an OEM or a product owner can incentivize other parties to collect and share data on product individuals.

The results of this study suggest that while significant challenges for implementation exist in the current industrial landscape, the applicability of blockchain technology to the problem of product-centric information management has so far been perceived narrowly in academia, largely overlooking its potential significance to sustained inter-industrial deployment. This observation supports the earlier findings of (Blossey *et al.*, 2019) where the authors state that the "[*supply chain*] *applications of blockchain technology mostly focus on efficiency improvements and risk mitigation from a single-firm perspective. – – However, this perspective largely omits the institutional innovation potential of blockchains reorganizing supply chains for collaborative ecosystem-based value creation.*"

The insights provided by this study regarding the incentivized deployment of blockchain solutions for product-centric information management may also help the deployment of similar distributed data sharing solutions intended for other purposes and other sectors of society. The conceptualization delineated in this paper may be especially helpful in cases where the aim is to establish auxiliary services and solutions for business processes that are not core to any of the participants involved. Furthermore, the conceptualized design could also enable an approach where data products on product individuals were manufactured to order, and the curated workflow of the participation protocol served as an index on where the data product could be requested. If successful in its deployment, due to its agnostic data ontology, the system could also be expanded to house a variety of all kinds of data products. Also, the technique could be utilized to manage data in other contexts than product data management, *e.g.* direct from design manufacturing.

7 Conclusion

Our study offers a new network-effect-driven perspective on how inter-industrial data sharing solutions could be established and maintained through a blockchain-based approach, including system development, deployment, and payment processing. In most contemporary design proposals for product-centric information management, the deployment and workflow structures of digital interactions are unilaterally controlled by the service provider who is also providing the underlying technical architecture. By disentangling the solution provision from the control of the data and the workflow, hindrances in the integrational development of inter-industrial digitalization could potentially be alleviated, thus enabling more widespread adoption. Further studies are encouraged for the inter-industrial perspective to product-centric information management, with a design focus on sustained solution deployment.

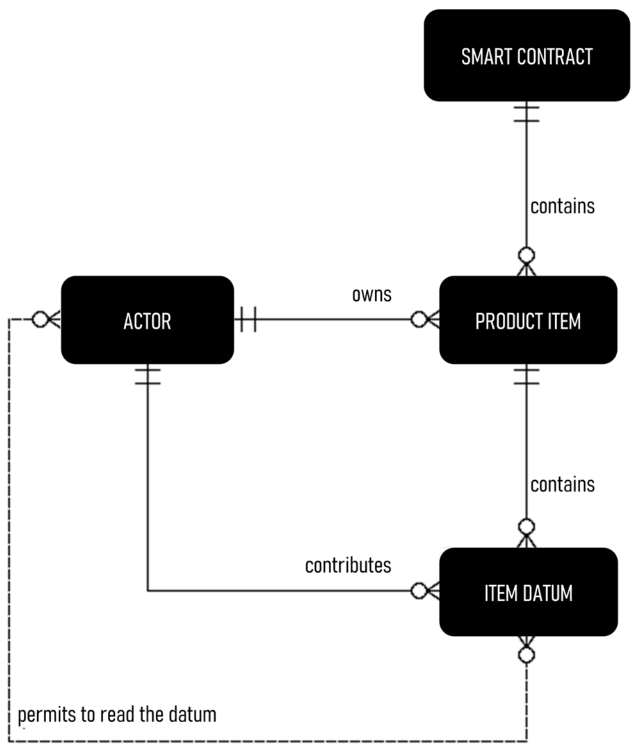
Appendix A: Protocol for blockchain-based deployment

In the following sections, we will present data model, and the different operations that allow the deployment of the loader crane according to the scenario described above. The complete and functional source code for the demonstration can also be found at (Valkama, 2020).

A.1 Product system design

The conceptual data model of the conceptualized system is illustrated in Figure A. The product system contains a collection of product items which are owned by actors such as manufacturers or dealers. The product items each contain a collection of item datums. Consequently, each datum added to a system has an originating actor who is thus considered as the contributor of the datum. Only the contributor of a datum can read the particular datum without cost while all other actors in the sys-

Figure A. The conceptual data model of the product system modelled as an Entity-Relationship (ER) diagram.



tem are subject to a fee to be able to access it. The actors who have paid the fee are represented in the figure as having the permit to read a datum.

The implementation of the conceptual data model in Solidity, the language used to describe smart contracts in the Ethereum blockchain platform, is shown below:

Product system model (Solidity code)

```
struct ItemDatum {
  address payable contributor;
  mapping(address => uint) permits;
  string datum;
}

struct ProductItem {
  uint itemId;
  address owner;
  mapping(string => ItemDatum) data;
}

uint itemCount;
mapping(uint => ProductItem) private items;
```

The actors in the system are represented simply as Ethereum addresses in the smart contract. This establishes a unique identity to each actor and allows for authentication and access control of the smart contract operations in the Ethereum platform. Furthermore, a simple associative array style data structure of string keys and (datum) values was chosen to represent the product item data. As per the objectives, this imposes minimal restrictions on how to structure and model the product item data, thus enabling different industries to develop their own standards. The requirement of using only textual formats for data also allows for better interoperability across systems and actors. Furthermore, the requirement also discourages polluting the product system with *e.g.* proprietary binary files that are of no use on a larger scale when considering the entire life cycle of a product item and the larger systemic perspective.

The next sections will cover the different operations that are required to implement the semantics of the smart contract, as described in the example scenario. In addition, JavaScript example code of how the smart contract could be called from the client side will be shown.

A.2 Creating a product item life cycle journey

Just as every loader crane in the physical realm goes through a journey of events over its life cycle, respectively, the life cycle of each corresponding product item object in the smart contract can be structured in the same manner. All the product items begin their life cycle journey in the smart contract when a manufacturer sends a transaction to the smart contract, requesting the creation of a new product item with the supplied manufacturing data:

Client side (JavaScript code)

```
createProductItem("4950", {serialNumber: 4950, modelSpecifier: "KPV"});
```

Upon receiving the request sent by the client, the smart contract stores a new product item to the blockchain with the manufacturing data and the sender of the transaction (the manufacturer) as its initial owner. Additionally, the smart contract sends an event, that can be subscribed to by clients, signalling the creation of a new product item:

Smart contract (Solidity code)

```
function createProductItem(
  string memory correlationId
  string memory _manufacturingData
) public returns (uint itemId) {

  uint newItemId = ++itemCount;
  ProductItem memory newProduct = ProductItem({
    itemId: newItemId,
    owner: msg.sender
  });
  items[newItemId] = newProduct;

  setItemDatum(newItemId, "manufacturingData", _manufacturingData);

  emit ProductItemCreated(newItemId, correlationId, msg.sender);

  return newItemId;
}
```

A.3 Transferring the ownership of a product item

When the ownership of a physical loader crane is transferred, the product item in the smart contract must also undergo a transfer of ownership so that the new owner can control the product item. The ownership transfer process is initiated by the current owner by sending a transferral request transaction from the client side to the smart contract, with the product item identifier and the Ethereum address of the new owner as parameters:

Client side (JavaScript code)

```
transferOwnership(4950, "0x485B48DB7e8c65E76178a4C080a7099A5780aA86");
```

Before executing the transfer of the ownership, the smart contract checks that the sender address of the transaction is the same as the address of the owner of the product item. If the sender is not the same as the owner, an error is returned, and the transaction is aborted. After ensuring that the sender is the owner of the product item, the new owner is assigned to the product item and the transaction completes successfully:

Smart contract (Solidity code)

```
modifier onlyOwner(uint productId) {
   require(
      msg.sender == products[productId].owner,
      "Operation permitted only by owner"
   );
   _;
}

function transferOwnership(
   uint _itemId,
   address _newOwner
) public onlyOwner(_itemId) {
   items[_itemId].owner = _newOwner;
}
```

A.4 Assigning new data to a product item

As a loader crane journeys through its individual life cycle, it goes through a unique sequence of transformative events. Respectively, the information contained in the product item must be updated to reflect these changes accordingly. To associate new data to the product item, the owner sends a transaction to the smart contract, using the product item identifier, the key identifying a particular datum, and the datum itself as parameters:

Client side (JavaScript code)

```
setItemDatum(4950, “latestInspection”, {date: “2020-04-21”, result: “ipfs://...”});
```

Upon receiving the request, the smart contract first checks that the sender address of the transaction is the same as the current owner and then updates the product item, associating the datum by its key. Additionally, the address of the sender is stored along the new datum so that the smart contract will later be able to identify the actor who has contributed the particular datum to the system:

Smart contract (Solidity code)

```
function setItemDatum(
  uint_itemId,
  string memory _key,
  string memory _datum
) public onlyOwner(_itemId) {
  items[_itemId.data[_key] = ItemDatum(msg.sender, _datum);
}
```

A.5 Paying to access product item data

If an actor wants to access a particular datum but is not its contributor, the actor must first pay a fee to obtain a right to access the datum. To this end, a transaction is sent from the client side with the product item identifier, the datum key and the payment amount as parameters:

Client side (JavaScript code)

```
payDatumFee(4950, "latestInspection", {value: "1000000000000000"});
```

Upon receiving the payment request, the smart contract first checks that the sender of the transaction is not the contributor of the datum. If the contributor and the sender are the same, the transaction is aborted. Otherwise, the smart contract will deposit the paid fee to the Ethereum address of the contributor and then issue access to the sender while also associating the timestamp of the current blockchain block with the permit:

Smart contract (Solidity code)

```
modifier onlyNotContributor(uint _itemId, string memory _key) {
  require(
    items[_itemId].data[_key].contributor != msg.sender,
    "Only applicable to actors who are not contributors of the datum"
  );
  _;
}

function payDatumFee(
  uint _itemId,
  string memory _key
) public payable onlyNotContributor(_itemId, _key) {
  require(msg.value == 1000000000000000, "Costs 0.001 eth");
  items[_itemId].data[_key].contributor.transfer(msg.value);
  items[_itemId].data[_key].permits[msg.sender] = block.timestamp;
}
```

A.6 Querying product item data

The product item data may be queried at various stages of the product item's life cycle by various different owners. Furthermore, queries can also be made by others actors with access to the smart contract deployment, such as public authorities or third-party integration systems. However, only the original contributor of a particular datum may access it without a cost, whereas other actors must pay a query fee to obtain access. To query data from a product item, a read query is sent from the client side with the product item identifier and the datum identifier as parameters:

Client side (JavaScript code)

```
getItemDatum(4950, "latestInspection");
```

Upon receiving the query request, the smart contract first checks whether the sender of the transaction is different than the contributor of the datum requested. If the sender and the contributor are the same, the requested datum is returned immediately to the sender. Instead, if the sender and the contributor differ from one another, the smart contract will check whether the sender has access associated with the datum, and in case access has not expired, the datum will be returned:

Smart contract (Solidity code)

```
function getItemDatum(
  uint _itemId,
  string memory _key
) public view returns (string memory datum) {

  if (msg.sender != items[_itemId].data[_key].contributor) {
    uint permitTimestamp = items[_itemId].data[_key].permits[msg.sender];
    require(permitTimestamp + leaseTimeSeconds >= block.timestamp, "No permit");
  }

  return items[_itemId].data[_key].datum;
}
```

Appendix B: Interview guide

TOPIC	KEY QUESTIONS
	Warm-up (1st and 2nd round)
BASIC INFORMATION	▪ Name, age, occupation?

EXPERIENCE	▪ In number of years, how would you describe your experience in:
	  ▪ product data systems?
	  ▪ blockchain technology?

CLARITY	▪ Do you have any questions about the concept?
SENTIMENT	▪ Other initial thoughts about the concept?
	Technical design (2nd round only)
PRODUCT EXAMPLE	▪ How do you feel about the loader crane product item and the industry setting specified for this demonstration?
PARTICIPATION PROTOCOL	▪ What do you think about the technical design of the participation protocol? ▪ Does it make sense to you? ▪ Is there something that jumps out as good or bad? ▪ Is there something that hasn't been considered? ▪ Is there something you would want to change about its design?
FEASIBILITY	▪ How do you see the practical implementability of this design? ▪ How do you feel about its ability to scale and to facilitate the complexity and heterogeneity of real-world product data?
OTHER	▪ Is there anything else you would like to comment about the technical design?
	Conceptualization (1st round: without product & industry context; 2nd round: with said context)
TECHNOLOGY	▪ What potential benefits and problems do you see with the use of a blockchain smart contract to facilitate the workflow of a product life-cycle journey?
GOVERNANCE	▪ The conceptualized PCIM platform has no centralized authority or platform provider. What benefits do you see following from this design principle? What about problems?
DATA FORMAT	▪ The concept does not specify any particular product data format. What are your thoughts on this? Benefits? Problems?

DEPLOYMENT	▪ What do you think about viability of the suggested method of platform deployment through an incentivized open-source participation protocol?
	▪ Could you also comment the cross-industrial aspect?
	  ▪ What kinds of problems might the concept solve in establishing a PCIM system?
	  ▪ What kinds of problems might the concept not solve in establishing a PCIM system?

PAYMENTS	▪ What do you think about the suggested method of incentivizing the provision of platform data through crypto-mining payments? ▪ The crypto-mining payment approach would, in principle, enable intelligent product items would be able to pay for the maintenance of their own product data with electricity and CPU power. What are your thoughts on this prospect? What are the benefits and the problems?
LONGEVITY	▪ The concept suggests that due to the incentivization mechanism, the conceptualized PCIM platform could outlive product individuals and even the companies that manufactured them. What benefits and problems do you see with this idea?
VERSATILITY	▪ Due to the open-access nature of blockchain systems, the concept should be able to maintain the product data workflow intact even in the case of dynamic supply chain structures. What benefits do you see to this approach? What about problems?
SHORTCOMINGS	▪ What do you consider the weakest aspect of the concept? ▪ Are there considerations which the concept fails to take into account?
	Delphi (2nd round only)
DELPHI	▪ Do any of these summarized key points in this list jump out to you as something you want to comment? For example, is there something in particular you strongly agree or disagree with?

Endnote

1 For additional information, see <https://docs.ipfs.io/introduction/>. Accessed on 21st of January 2020.

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Article 3

Distributed Governance in Multi-Sided Platforms: A Conceptual Framework from Case: Bitcoin

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Original publication:

Mattila *et al.* (2018). Distributed Governance in Multi-sided Platforms: A Conceptual Framework from Case: Bitcoin. In: Smedlund A., Lindblom A., Mitronen L. (eds) Collaborative Value Co-creation in the Platform Economy. Translational Systems Sciences, Vol 11. Springer, Singapore.

Abstract

Over the last decade, blockchain technology has facilitated a method by which a network of equipotent and equally privileged peers can jointly maintain and edit databases in an entirely decentralized manner, without any kind of an intermediary exhibiting unilateral control. As a consequence it has enabled the creation of a new type of multi-sided platform architecture with distributed governance. As the different platform provision functions are opened to free market competition rather than monopolized by a single entity, the monopoly-like pricing structure typical of platforms is overhauled. Instead, blockchain-enabled distributed platforms appear to share value more evenly between the all the different market sides connected to the platform. Our analysis reveals that blockchain technology adds new considerations to how multi-sided platform architectures should be perceived and analyzed.

Keywords

platforms, multi-sided markets, governance, blockchain, Bitcoin, cryptocurrency

1 Background introduction

In recent years, blockchain technology[1] has facilitated a method by which a network of equipotent and equally privileged peers can jointly maintain and edit databases in an entirely decentralized manner, without any kind of an intermediary exhibiting unilateral control. As a consequence, blockchain technology has enabled the creation of a new type of platform architecture with distributed governance. Rather than a single intermediary constructing and governing the platform, these blockchain-enabled distributed platforms utilize internal joint revenue models to incentivize open participation in all the different platform provision functions. This has enabled the provision of similar digital platform service systems as with a single platform provider but in a completely distributed manner (see Gawer & Cusumano, 2002; Boundreau & Hagiu 2008; Gawer, 2009; Hagiu, 2014; Hagiu & Wright, 2015; van Alstyne *et al.*, 2016, Parker *et al.*, 2016).

As the platform provision functions are opened to free market competition rather than monopolized by a single entity, the monopoly-like pricing structure typical of platforms where the platform provider captures most of the value is overhauled. Instead, blockchain-enabled distributed platforms appear to share value more evenly between the all the different market sides connected to the platform: application developers, users, miners, nodes and platform developers alike.

A considerable amount of literature has been published on platforms. These studies offer various definitions for a platform[2]. In the first stage of development, the terms 'platform' and 'product platform' were used by R&D scientists to illustrate the creation of new-generation products and services or a new product family for use as a basis for a range of product and service variants offered to customers in one-sided and two-sided markets (Gawer & Cusumano, 2002; Eisenmann *et al.*, 2006; Gawer, 2009, van Alstyne *et al.*, 2016).

In the second stage of development, a school of technology researchers defined a platform as a control point and as a gate-keeper role in industrial networks used for earning revenues without actually creating value, while at the same time economically damaging the network as a whole (For control point discussion, see Cusumano & Selby, 1995; Cusumano & Yoffie, 1998; Gawer, 2009; van Alstyne *et al.*, 2016; for gate-keeper role discussion, see Ballon, 2009a, 2009b; Ballon & Van Heesvelde, 2011; Pon *et al.*, 2014).

In the third stage of development, industrial economists defined the term 'platform' as a medium for conveying products, services and related transactions—as a marketplace between two or more different market sides (Rochet & Tirole, 2003; Parker & van Alstyne, 2005; Rochet & Tirole, 2006; Boudreau & Hagiu, 2008; Rysman, 2009; Hagiu & Wright, 2015; van Alstyne *et al.*, 2016).

Numerous definitions have been proposed for multi-sided markets over the years. One of the earliest definitions revolved around the presence of indirect network effects between two or more groups of platform participants (Katz & Shapiro, 1994; Caillaud

& Jullien, 2003; Armstrong, 2006). Another approach has been to define two-sided markets through their pricing structure. According to this view, in a multi-sided market, profits are not only affected by prices—they are also essentially affected by how the prices are allocated to different participant groups (Rochet & Tirole, 2003; Parker & van Alstyne, 2005; Rochet & Tirole, 2006; Boudreau & Hagiu, 2008; Rysman, 2009).

Later on, Hagiu and Wright (2015) argued that a multi-sided platform is simply one which enables direct interactions between two or more market sides, each of which is somehow associated with the platform. Thus, a multi-sided platform typically comprises three kinds of elements: 1) a stable core, 2) a dynamic set of complementary assets, and 3) the design rules acting as interfaces between them. The generic idea behind platforms is that by facilitating the integration of various stable and dynamic elements in a manner carefully coordinated by the design rules, platforms can achieve a higher degree of innovative dexterity in some areas of interest while still preserving economies of scale in others (Teece, 1986; Baldwin & Woodard, 2009; Boudreau & Hagiu, 2009; Bourdeau, 2010; Parker *et al.*, 2016).

Market structures can also be described as fixed-role and switch-role markets (Aspers, 2008). Subsequently, the concept of a platform was extended to include social, primarily contractual boundary resources as well as technical boundary resources (Gawer, 2009; Eisenman *et al.*, 2008; Bourdeau, 2010; Yoo, 2010; Ghazawneh & Henfridsson, 2013). Additionally, reference should be made to the research on technology platforms initiated in the 1990s as well as compatible and competing standards (Cusumano & Selby, 1995; Kim & Kogut, 1996; Cusumano & Yoffie, 1998) and to the research on platform governance (Schilling, 2005; Tiwana *et al.*, 2010; Tiwana, 2014).

Schilling (2005) defines platform governance as "the mechanisms through which a platform owner exerts influence over app developers participating in a platform's ecosystem". Boudreau and Hagiu (2009) analogize platforms to public regulators, with the exceptions that platforms typically regulate with an interest of maximizing profit by controlling prices, access and interactions on the platform, and that they usually exhibit regulatory behavior in the domain of technical design, system architecture, and technical relationships. Moreover, Parker and Van Alstyne (2014) define governance as the set of rules concerning who gets to participate in an ecosystem, how to divide the value, and how to resolve conflicts.

On a general level, the prevalent definitions of platform governance refer to the interaction between the platform provider and any agents who contribute to the service offering of the platform externally, from outside of the platform itself. While such *external governance* remains very relevant for research, in order to fully describe blockchain-enabled distributed platforms, the definition of platform governance must be expanded to include the mechanisms of *internal governance*; these are the mechanisms through which the providers of a multi-provider platform exert influence over other providers participating in the provision of the same platform. (Schilling, 2005; Tiwana *et al.*, 2010; Tiwana, 2014)

Parker *et al.* (2016) and de Reuver *et al.* (2017) propose that further studies on platform governance may yet provide answers to some of the open questions in platform literature, e.g. how to design balanced internal governance systems in multi-sided platforms to ensure fair operation. The internal governance structures in blockchain-enabled distributed platforms have not yet been thoroughly explored in the context of this open question in the multi-sided platform literature. By performing a case study on the most prominent blockchain-enabled distributed platform in existence—namely the Bitcoin cryptocurrency network—this chapter makes an effort to determine whether blockchain architectures can constitute multi-sided platforms as delineated in the platform literature. The motivation for this analysis is to determine whether blockchain architectures are relevant to this open research question regarding more balanced internal governance systems in multi-sided platforms. Having established that these systems are indeed relevant, we then proceed to describe how the internal governance structure is organized in these new kinds of distributed platforms.

The aim of this study is to answer the following research questions:

1) To what extent is the concept of multi-sided platforms, as delineated in platform literature, compatible with blockchain architectures?
2) What kinds of platform governance structures do blockchain architectures exhibit when observed through this framework of multi-sided platforms?
3) What are the potential wider implications of blockchain governance structures on multi-sided platforms research?

Our analysis reveals that blockchain architectures add new considerations to how multi-sided platforms should be perceived. Firstly, in blockchain-enabled distributed platforms, not only have the product and service innovations pertaining to the platform been externalized, but the entire platform provision has been distributed across various market sides. Therefore, blockchain-enabled distributed platforms introduce new categories of interaction between platform participants. Secondly blockchain-enabled distributed platforms introduce new models of platform governance. Furthermore, as no formal decision-making protocols are in place, an informal negotiation process takes place involving a scheme of theoretical attacks and countermeasures used as bargaining chips against other market sides. Thirdly, blockchain-enabled distributed platforms seem to have introduced a new method of platform monetization. Much like contemporary multi-sided platforms, blockchain-enabled distributed platforms also employ split revenue schemes but in a more equilateral manner and without monopolistic pricing structures.

The remainder of this chapter continues as follows. The second section explains the methodology of the study. The next section describes platform characteristics and the internal governance structure of blockchain-enabled distributed platform mechanism in the light of platform literature. The fourth section presents the findings of the research focusing on the two key themes 1) do blockchain-enabled distributed platforms meet the criteria of a multi-sided platform and 2) the applicability of Tiwana's (2014) framework on platform governance. We conclude this chapter with a short discussion on the implications for future research.

2 Research methodology

The theoretical positioning of this research is mainly conceptual in nature. In academic literature, conceptual papers are ones quintessentially characterized by an integrational approach. Rather than emphasizing empirics, conceptual papers tend to fixate on providing cross-disciplinary insights and bridging theories. While the focus of conceptual research is typically much narrower in scope than that of theory-building research, a well-drafted conceptual paper may also contribute to theory by pointing out interesting relationships, improving theoretical coherence, and proposing new directions and perspectives for further research. (Gilson & Goldberg, 2015; Sutton & Staw, 1995)

The chosen methodology for this study is a case study design. Case studies can be utilized for several different purposes, e.g. to test existing theories, to generate new ones, or simply to describe phenomena (Eisenhardt, 1989). As its case of analysis, this paper examines the most prominent blockchain architecture in existence at this time: the Bitcoin cryptocurrency network. In the first part, we test the applicability of the multi-sided platform theory to blockchain architectures by super-imposing the conceptual framework of multi-sided platforms onto the Bitcoin network. The second part of the analysis makes an effort to describe the phenomenon of internal and external governance in blockchain architectures from the perspective of multi-sided platforms. The governance mechanisms are delineated by using the classification of Tiwana (2014) on platform governance as a framework.

Tiwana (2014) distinguishes three dimensions of platform governance: decision rights, control, and pricing policies. Decision rights pertain to setting goals for what the participants should be able to achieve and how. These rights are divided into two dimensions, with two categories each: 1) platform decision rights vs. application decision rights, and 2) strategic decision rights vs. implementation decision rights. Control is used to ensure that the behavior of all the different participants is in line with those goals. Tiwana (2014) lists four different categories of control: input control, output control, process control, and relational control. Pricing policies dictate how the value created by this aligned collaboration will be shared. They describe the incentives that are used to attract all the different markets sides and to encourage them to participate in the platform ecosystem.[3]

In addition to literary references, the technical understanding on blockchain technology in this chapter also draws from non-directive interviews with industry experts from companies such as IBM, BitPay, Blockstream, Vaultoro, Colu, Bitreserve, Google, 21, Stellar, Monax, Ascribe, Prasos and Fortum in 2015–2017.

3 Analysis

3.1 Platform characteristics in blockchain networks

3.1.1 Network effects

In economics, a network effect describes a situation in which the value that a user gets from using a system depends on how many other participants the system has. This dependency can be either *positive* or *negative*. Direct network effects occur when increased use of a product or a service benefits or harms the users of that particular product or service. In the online gaming community, for example, players experience direct network effects from additional players joining the gaming environment. Indirect network effects are in question when increased use of a product or a service benefits or harms the users of a different product or service. To follow with the earlier example, in the online gaming community, the players benefit indirectly from the presence of game developers participating in the community, and vice versa. (Katz & Shapiro, 1994; Caillaud & Jullien, 2003; Armstrong, 2006)

In platform literature, network effects have been mentioned as one of the key characteristics of multi-sided platforms. Likewise, blockchain-based distributed platforms also live and die by network effects. In fact, the successful fostering of network effects is even more important in blockchain-enabled distributed platforms than in other platform types, because the security and the technical functionality of the platform are to a large extent based on them (See Nakamoto, 2008).

The robustness of a blockchain network typically grows stronger with every additional miner and node, thus fortifying the network against malevolent attacks that, if successful, could ultimately render the entire platform useless (Nakamoto, 2008; Laszka *et al.*, 2015; Yli-Huumo *et al.*, 2016). As this makes the platform more stable and safer to operate, the logical consequence is the attraction of more users to join the platform (see e.g. Vasek *et al.*, 2014). Respectively, increased user activity makes the platform financially more appealing to miners and application providers, as more paying customers translates into more opportunities for business and profit (Kroll *et al.*, 2013; see also Alabi, 2017). Similarly, a higher number of application providers can be postulated to draw more platform developers to the platform, as this translates to better funding opportunities (van Wirdum, 2016). The addition of more developers, in turn, increases usability and security, thus likely attracting more users, miners and application providers, and so on (see e.g. Alabi, 2017).

3.1.2 Multi-sided markets

In platform literature, one characterization of multi-sided platforms is that they operate in *two-sided*—or more generally speaking, *multi-sided markets*. A market is said to be multi-sided if more than one market side is crucial to the outcomes of interest, and the market sides exhibit network-effect-like externalities between them (Rochet & Tirole, 2003; Parker & van Alstyne, 2005; Rochet & Tirole, 2006; Eisenmann *et al.*, 2006; Boudreau & Hagiu, 2008; Rysman, 2009; Hagiu, 2014; Hagiu & Wright, 2015; van Alstyne *et al.*, 2016).

Blockchain-based distributed platforms emerge from the collaboration of several different types of actors. This collaboration can be described as a multi-sided market where some of the market sides are platform providers and some of them are platform users. In the Bitcoin platform, five market sides can be distinguished: the users, the application providers, the miners, the nodes, and the platform developers.

Users are the actors whose main motive for participating in the distributed platform is to make use of its practical functionality. Users may be looking to transfer funds over the internet, for example. Alternatively, they may be interested in acquiring some of the cryptocurrency tokens native to the platform with the intent to hold them as an investment for financial gain. Users can access the platform either by going through the services of application providers, or by setting up their own node (see below) and connecting it to the network (Athey *et al.*, 2016).

Application providers participate in the distributed platform by building products and services on top of it which extend the functionality and the usability of the underlying platform. In doing so, the application providers introduce complementarities which further enhance the network effects of the platform. Most often the application providers monetize their business by charging service fees from the users. Wallet service providers and cryptocurrency exchange services, for example, fall into this category (Athey *et al.*, 2016).

Miners are essential to the operation of the network. They handle the data-entries and the transactions between the users of the platform, and provide security by partaking in the consensus-forming process of the network. By constantly solving concatenated mathematical problems in a cryptographic process known as *hashing*, the miners produce *proof of work*: a testimony to the fact that the content of the distributed database is authentic. As the hashing process consumes CPU power, the miners are incentivized to partake in the process by issuing them new cryptocurrency as *mining rewards*, as well as *transaction fees* charged from the users (Böhme *et al.*, 2015; Gasser *et al.*, 2015; Filippi & Loveluck, 2016; Dimitri, 2017).

Nodes are the computers/software clients which form the actual blockchain network. Each one of them individually maintains the distributed database which underlies the distributed platform. The nodes are also in charge of enforcing the consensus rules of the network by validating and propagating the new blocks produced by the miners for the blockchain. Each node operates autonomously, irrespective of other nodes or platform participants. Nodes can either be *full nodes* or *simplified payment verification (SPV) nodes*. Each full node maintains a full copy of the entire blockchain, making them the backbone of trustless security in the network. SPV nodes only store block headers, making them less independent but much lighter to run. (Nakamoto, 2008; Cawrey, 2014; Filippi & Loveluck, 2016)

Platform developers work on the technical design of the Bitcoin protocol. They formulate and propose adjustments to the technical and social boundary resources that govern the interactions that take place on the platform. Early stage developers can monetize their development efforts by holding an initial investment of tokens within the platform. As the amount of activity on the platform increases, so does the demand for the tokens, consequently driving up their purchasing power. At later stages, platform developers can also be supported directly by consortiums of large-scale application developers. (Filippi & Loveluck, 2016; van Wirdum, 2016)

It is noteworthy that the market sides presented here are not mutually exclusive. For example, miners and application providers may run nodes to increase the robustness of the network, and platform developers may double up as users in the investor role. Any individual can freely join any number of the market sides, as long as they adhere to the predetermined protocols. To express the matter in the terms of platform literature, the Bitcoin platform constitutes switch-role markets rather than fixed-role markets (Aspers, 2008).[4]

3.1.3 Complementarities

In platform literature, the presence of complementarities has been considered one key characteristic of multi-sided platforms. Goods and services are said to be complementary to one another if the utility offered by one greatly depends on the consumption of the other. One classic example of a complementarity is the relationship between a rowing boat and a pair of oars: these assets offer much higher utility when used together compared to when using them separately. (For more information on complementary assets, see the seminal work of Teece, 1986; 1988; Yoffie & Kwak, 2006; Dahlander & Wallin, 2006; Gawer & Henderson, 2007).

The complementarities in blockchain-enabled distributed platforms do not only manifest themselves in the external goods and services attached to the platform, but also internally within the platform itself. As blockchain-enabled distributed platforms do not have a distinct platform owner, they require the collaboration of various market sides to produce all the necessary platform provision functions (Filippi & Loveluck, 2016). This collaboration can only produce a functional distributed platform if all the required provision functions are addressed.

3.1.4 Boundary resources

In platform literature, boundary resources are the operational regulations and technical tools and interfaces governing the interaction between the platform owner and the platform participants. They can be used either to encourage platform development or to restrict it in places where the platform owner wishes to maintain control over the developmental direction of the platform. These resources are sometimes divided into *technical* and *social* boundary resources (Gawer, 2009; Bourdeau, 2010, Yoo *et al.*, 2010; Ghazawneh & Henfridsson, 2013).

Technical boundary resources govern the technical interactions between platform participants. In distributed platforms they manifest themselves in the operational principles of the distributed consensus network which underlies the platform. These boundary resources define operational features, such as how the nodes of the network connect and communicate to one another, what kind of a consensus protocol is employed by the network, and what are the prerequisites for partaking in the platform provision functions. (Nakamoto, 2008)

Social boundary resources manifest themselves as the predetermined framework for social interaction on the platform, e.g. pre-specified terms of agreement for application developers, or revenue-split models between participants (Gawer, 2009). In distributed platforms, the social boundary resources consist of the business and contract rules governing the content of the distributed database that the distributed consensus network maintains. These rules define what kinds of modifications can be done to the database, by whom and in what manner. For example, in cryptocurrency platforms users are typically not allowed to make payments that would exceed their account balance (see *e.g.* Filippi & Loveluck, 2016).

The social boundary resources of blockchain-enabled distributed platforms also outline the joint monetization models, e.g. how the mining rewards are added to the total money supply of the platform. It is noteworthy, however, that in blockchain-enabled distributed platforms, these split-revenue schemes are algorithmically governed, rather than decided by a platform owner. (Dimitri, 2017; Böhme *et al.*, 2015) It seems to be the case then that blockchain-enabled distributed platforms bring some of the boundary resources formerly considered more social in nature into a more technical domain.

Contemporary platforms are also differentiated from blockchain-enabled distributed platforms by the fact that whereas the former are provided by one party, distributed platforms, by definition, have multiple equipotent and equally privileged platform providers. Therefore, distributed platforms also have a completely new area where boundary resources apply: the internal interactions between one platform provider and another platform provider. These inter-provider boundary resources include many familiar ones, such as APIs, SDKs and technical documentations, but also some completely new ones, such as a consensus protocols and the algorithmically defined game-theoretical incentivization structures mentioned above (Nakamoto, 2008).

3.2 Mechanisms of internal governance

3.2.1 Decision rights

Tiwana (2014) divides decision rights into two dimensions, with two categories each: 1) platform decision rights vs. application decision rights, and 2) strategic decision rights vs. implementation decision rights. Platform decision rights pertain to decisions relating to the platform, whereas application decision rights pertain to decisions relating to the complementary assets of the platform. Strategic decision rights refer to the right to determine *what* the platform or a complementary asset should be able to achieve, while implementation decision rights are related to determining how those goals should be accomplished.

Tiwana (2014) measures these four categories of decision rights on a gradient scale from full centralization to full decentralization. Baran (1964), however, differentiates between three configurations for communications networks: centralized, decentralized, and distributed. In order to more accurately describe the allocation of decision rights in blockchain-enabled distributed platforms, this paper expands Tiwana's (2014) gradient scale accordingly to include these three configurations.

Table 1. Decision rights in Bitcoin

	CENTRALIZED	DECENTRALIZED	DISTRIBUTED
PLATFORM STRATEGIC		✓	
PLATFORM IMPLEMENTATION		✓	
APPLICATION STRATEGIC			✓
APPLICATION IMPLEMENTATION			✓

The problem with trying to establish joint platform strategic decision-making processes for blockchain-enabled distributed platforms (e.g. democratic voting) is that there is no clear and objective way to measure the support for a strategy amongst all the different platform providers and participants. Moreover, no single faction or individual has the power to dictate platfrom strategy on their own without sufficient support from the others (Filippi & Loveluck, 2016; Gasser *et al.*, 2015; Kroll *et al.*, 2013). Therefore, the different market sides must communicate with one another to negotiate strategic platform decisions and their implementations, despite the fact that no structured forum or protocol exists for such negotiations at this point in time.

So, in theory, Bitcoin is anarchistic in governance, as no single platform owner is in control of the system, and no formal mechanisms of multi-party decision making are in place. A more detailed examination, however, reveals that some *de facto* structure exists regarding how platform decision rights are allocated within the system (Kroll *et al.*, 2013; Gasser *et al.*, 2015; Filippi & Loveluck, 2016). For example, miners and nodes can signal their support by running different client versions and developers can signal their support by committing to different development projects (Gasser *et al.*, 2015; Srinivasan & Leland, 2017).

It has been speculated by some that more formal protocols for strategic platform decision-making may be seen in the future. For example, anonymous cryptocurrency-based voting mechanisms may be considered for measuring how much support different planned strategies have in the platform ecosystem. (Consensus, 2017)

The platform implementation decisions in Bitcoin are decentralized rather than distributed in nature, as in practice the platform developer communities have great pre-eminence in what kinds of implementation proposals are brought forward in the platform ecosystem. (Kroll *et al.*, 2013; Gasser *et al.*, 2015) It is mainly up to the miners and the nodes to decide which proposals are accepted—other parties' decision rights in this respect are mostly manifested in their ability to affect the decision making of the aforementioned two market sides (Kroll *et al.*, 2013; Atzori, 2015; Filippi & Loveluck, 2016).

As Bitcoin is based on a *permissionless* blockchain architecture, no permission is required from any party to become a part of the network (Filippi & Loveluck, 2016). Therefore, application-related decision rights are completely distributed across the individual application providers and their respective developers.

3.2.2 Control

Output control, or *metrics*, refers to the mechanisms of rewarding or penalizing the platform participants on the basis of their performance against some pre-defined target performance metrics (Ouchi, 1979; Tiwana, 2014). In modern day platforms, explicit forms of output control are somewhat rare, as most platforms simply maintain one output criterion: the survival and success of their complementary assets in the free market competition environment (Armstrong, 2006; Bester & Krähmer, 2008).

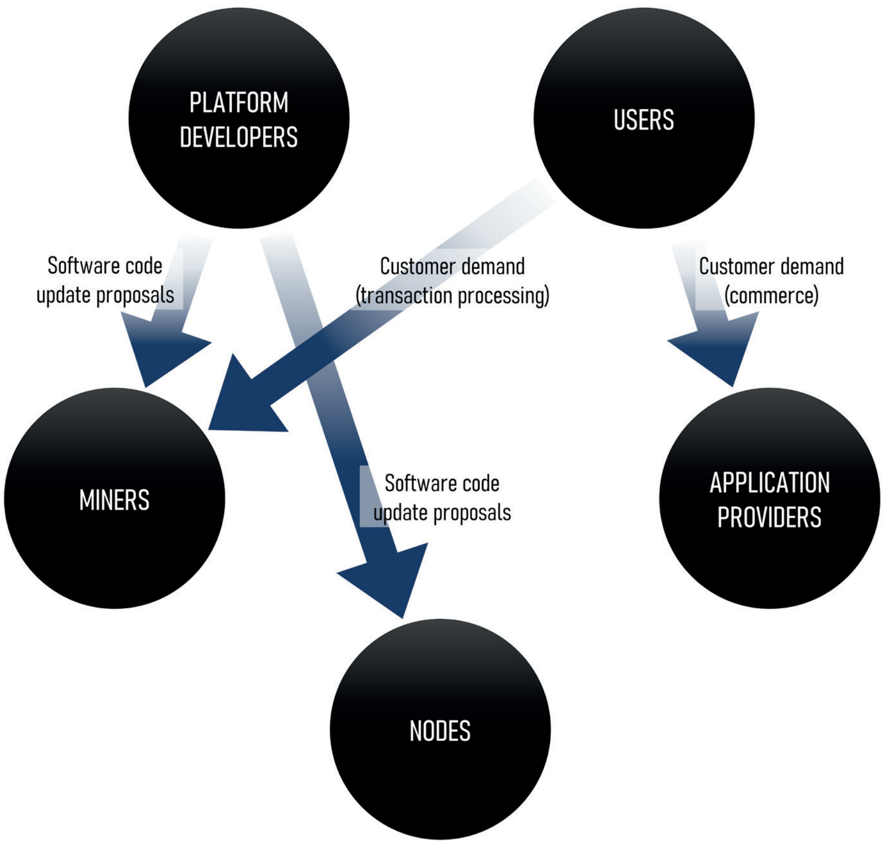
In Bitcoin, output control is mainly exercised by users and platform developers (see Figure 1). While the platform developers cannot force anyone to run their software, they can make proposals for new source code implementations.

Blockchain-enabled distributed platforms rely on open source code. Therefore, in theory, anyone could write and implement their own version of the code, as long as it adheres to the consensus protocol of the network (Gasser *et al.*, 2015; Filippi

& Loveluck, 2016). In practice, however, most if not all of the seriously considered suggestions for new source code implementations tend to come from the Bitcoin developer community. Therefore, the developer community has a great amount of control over what kinds of source code modifications are suggested to the network and what kinds of performance metrics and reward schemes they entail. (Kroll *et al.*, 2013; Atzori, 2015; Gasser *et al.*, 2015; Filippi & Loveluck, 2016)

The source code designed by the platform developers dictates what kind of a consensus algorithm the network uses to maintain integrity and how the mining incentives are configured (Kroll *et al.*, 2013; Gasser *et al.*, 2015; Filippi & Loveluck, 2016). As the profitability of the miners' business operations crucially depend on these factors, the platform developers have some output control over the miners (Torpey, 2016a; Torpey, 2016b). The nodes also run the code designed by the platform developers, and therefore they are also subject to the output control, even if they are not so crucially dependent on the decisions made (Gasser *et al.*, 2015).

Figure 1. Output control in the Bitcoin platform.

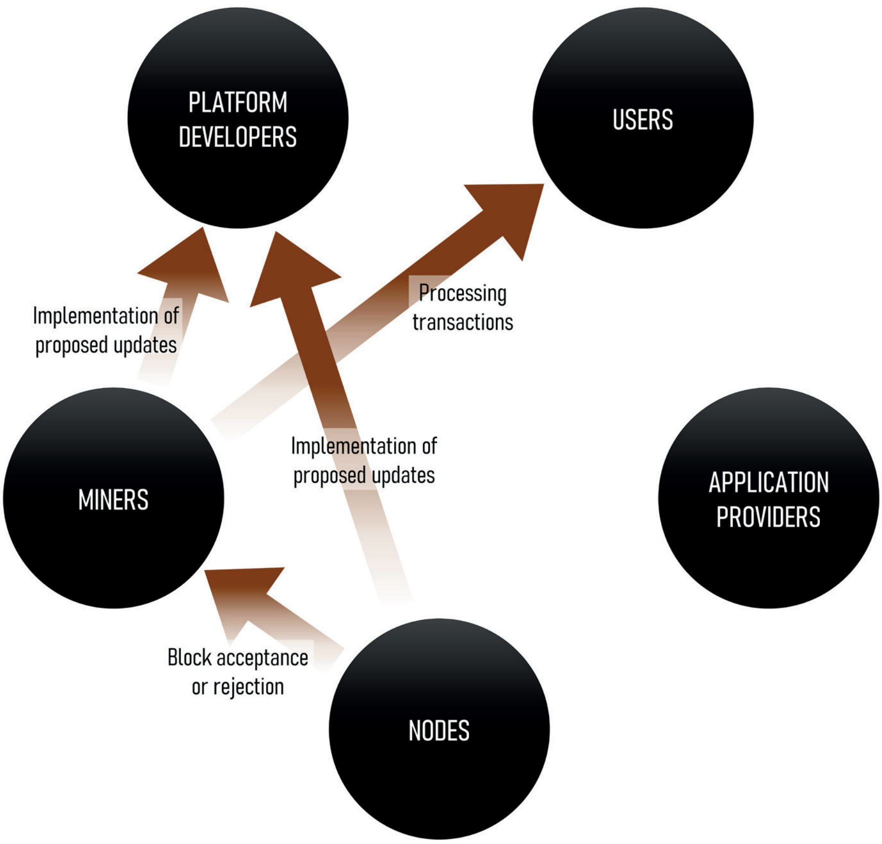


When the platform developers write new versions of the network's client software, they can propose three kinds of alterations: ones that add new consensus rules to the network (*soft forks*), ones that remove or replace old consensus rules from the network (*hard forks*), and ones that do not affect the consensus protocols one way or the other. The more drastic the proposed changes to the consensus rules are, the more difficult it is to get them approved (Croman *et al.*, 2016).

The users exercise output control over the miners in the sense that they provide the demand and the free-market competition environment for the miners' services. A miner must be able to perform a competitive amount of computational work for a set market price in order to turn a profit.

Input control, or *gate-keeping*, is the enforcement of some pre-defined, objective criteria as a prerequisite for granting entry into the platform ecosystem. Typically the term has been used in reference to the platform owner exercising control over what kinds of application developers it allows into its cohort of complementary asset pro-

Figure 2. Input control in the Bitcoin platform.



viders (Cardinal, 2001; Evans *et al.*, 2006; Boudreau, 2010; Tiwana, 2014). While no such control exists in the Bitcoin platform in this sense (Parker *et al.*, 2016), input control is at play within the internal governance mechanics of the Bitcoin network itself.

The input control in Bitcoin is mainly exercised by the miners and the nodes, both of whom run the software developed by the platform developers (see Figure 2). As miners and nodes are free to decide which versions of the platform software they want to use, they are very influential as groups in determining what development features are accepted as a part of the platform and which ones are not (Kroll *et al.*, 2013; Atzori, 2015; Filippi & Loveluck, 2016).

The miners also have input control towards users in the sense that they have the power to decide which pending transactions are entered into the blockchain and which ones are not (Dimitri, 2017). This form of control also has some characteristics of output control. The miners are limited in their capacity to add transactions into the blockchain by the block size specified in the consensus rules of the network. As the pending transactions have tips called *transaction fees* attached to them by the users, the miners have an incentive to attach the highest bidding transactions to the blocks first (Dimitri, 2017; Kroll *et al.*, 2013; Catalini & Gans, 2016). This creates a free-market competition environment where the users must provide adequate compensation for the service of the miners in order to have their service request fulfilled over other service requests.

Another form of input control in Bitcoin is that exercised by the nodes over the miners. As the nodes are effectively in charge of enforcing the consensus protocol of the network, they as a group have the power to decide which blocks proposed by the miners are accepted as a new part of the blockchain and which ones are rejected.

Process control pertains to rewarding and/or penalizing application developers for following prescribed methods and procedures of development. This can be so as to ensure interoperability with the rest of the platform, for example (Tiwana, 2014).

Process control is exercised in the Bitcoin network by users, application providers, and to some extent also miners (see Figure 3).

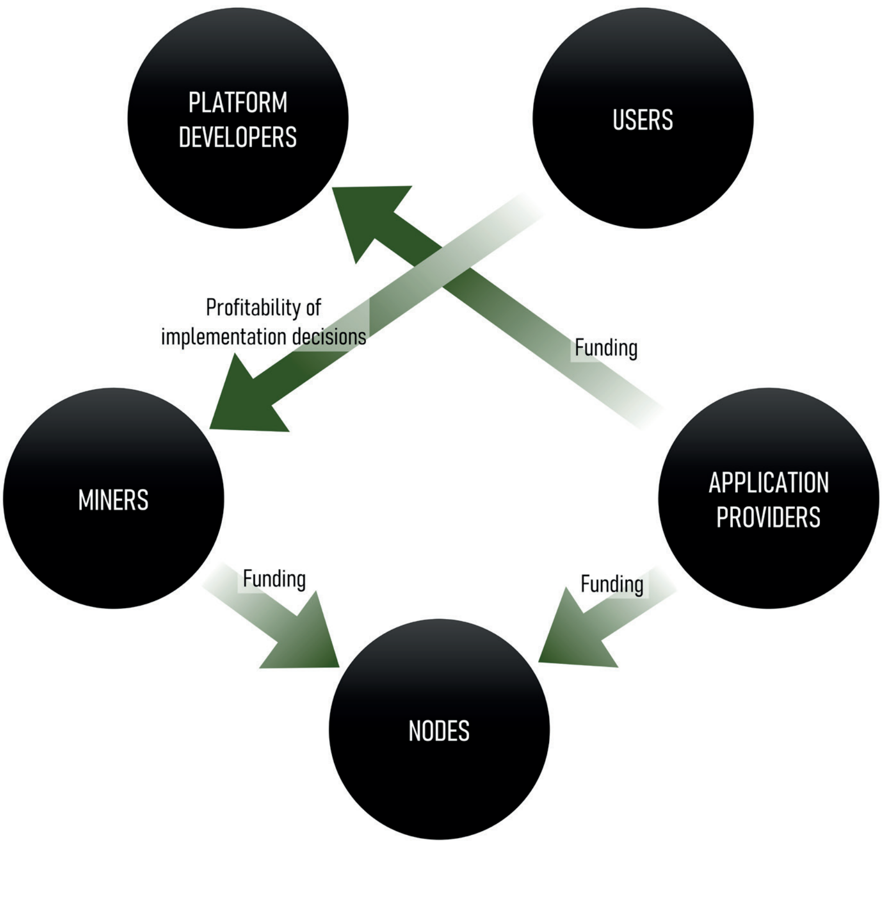
The platform developer community receives funding for their work from the application providers who have built their businesses on top of the Bitcoin platform and therefore depend on its development. This gives application providers some leverage over platform developers in determining what kinds of features should be incorporated into the source code and how the development should take place.

The same kind of a situation applies to nodes. Nodes are not compensated for their efforts through revenue split models in the same way as miners are, so they depend entirely on the good will of their respective owners to be set up and to have their operational costs covered. For this reason, the most reliable nodes of the network are usually maintained by parties who have the strongest vested interest to pay for them—that is, the market sides with the strongest ability to profit directly from participating in the platform: the application providers and miners (See Hagiu, 2014).

This gives them some degree of process control over what kinds of software updates the nodes will support, for example.

Perhaps the strongest position of process control, however, is held by the users over the miners. The motivation of the miners for participating in the platform is to make profit through transaction fees and block rewards, both paid out in the cryptocurrency tokens native to the platform. As stated above, the miners and the nodes have input control over the platform developers in deciding which software updates get implemented. However, if the miners choose to implement software code alterations that are not to the liking of the users, they will sell off their cryptocurrency tokens, lowering the exchange rate of the cryptocurrency, which in turn will directly affect the mining profitability (Athey *et al.*, 2016). The same process control mechanism also discourages minorities of the miners from implementing consensus-breaking software updates, or so-called *hard forks,* which would fragment the network into a larger number of smaller networks. (Reijers *et al.*, 2016)

Figure 3. Process control in the Bitcoin platform.



Relational control or *clan control* manifests itself in the shared norms and values held by the platform participants (Ouchi, 1979; Kirsch, 1997; Tiwana, 2014).

The cryptocurrency tokens used in blockchain-enabled platforms provide a strong mechanism for *relational control* (see Figure 4). They can be freely exchanged with conventional currencies and thus acquired by anyone who so pleases (Athey *et al.*, 2016). The cryptocurrency serves as a medium of internal and external co-operation in the platform ecosystem and it facilitates the incentivization of various participants by enabling a split revenue model for open participation (Catalini & Gans, 2016; Böhme *et al.*, 2015).

As the tokens circulated within the ecosystem are scarce, and as the transactions within the platform are settled in these tokens, increased activity in the platform ecosystem increases their demand, as described by the quantity theory of money:

$$M \times V = p \times q$$

where
M = the total amount of cryptocurrency tokens in circulation
V = the velocity of circulation
p = price level in the platform ecosystem
q = financial activity in the platform ecosystem

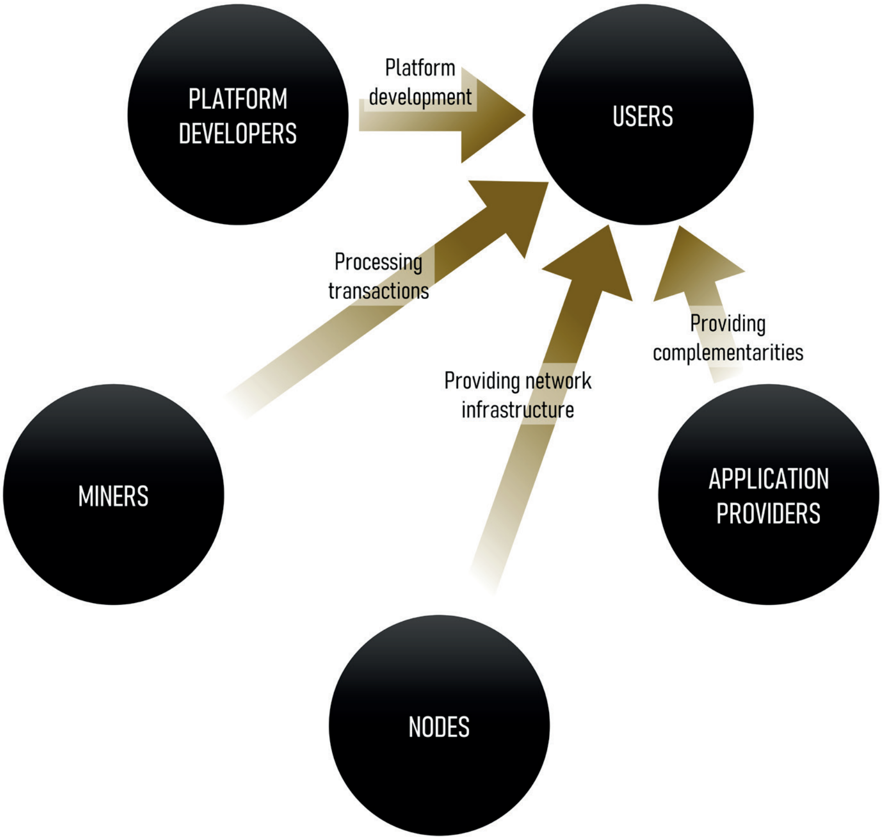
The rules and restrictions on minting new cryptocurrency tokens are governed by the source code of the client software on which the blockchain network operates. Therefore, how and by whom these tokens can be minted varies from system to system. Usually, however, the minting of new tokens is algorithmically restricted, and therefore the total amount of tokens (M) is practically finite at any given moment (Böhme *et al.*, 2015).[5]

The velocity (V) at which cryptocurrency tokens circulate in the ecosystem is limited by two factors: the average transaction value, and the transaction throughput capacity of the network. The average transaction value is dictated by the types of financial activity within the platform ecosystem. Therefore, unless major changes occur in the ways and in the purpose for which the platform is utilized, the average transaction value can be expected to remain relatively stable.

Blockchain ledgers usually rely on a method where a new standard-sized block is added to a blockchain at more or less frequent intervals. While the throughput can be increased by a majority decision amongst the participants to increase the block size, under normal operating conditions the capacity can be assumed to be fixed.

As financial activity on the platform (q) increases, it then follows from these assumptions that the only way for the equation to hold true is if the price level (p) decreases—that is, the value represented by each token must rise. Through this dependency and its projected growth development, the cryptocurrency tokens provide an investment vehicle which reflects the amount of activity on the platform ecosystem

Figure 4. Relational control in the Bitcoin platform.



as directly monetizable value. Therefore, anyone in possession of these cryptocurrency tokens will find their goals and values aligned towards fostering the growth and the network effects of the platform ecosystem as much as possible (Alabi, 2017; Catalini & Gans, 2016; Athey *et al.*, 2016).

3.2.3 Pricing policies

Since blockchain-enabled distributed platforms do not have a centralized platform provider, they are not prone to monopoly behavior with their pricing policies, as is often the case with contemporary platforms (Parker *et al.*, 2016).

The Bitcoin cryptocurrency platform uses revenue split schemes to incentivize collaboration amongst the platform providers. Partially these revenue splits are determined by free-market competition within the market sides engaged in platform provision. Some revenue splits are determined algorithmically in the source code and the consensus protocols of the network.

As mentioned earlier, maintaining consensus in blockchain architectures requires miners to produce a proof-of-work. This can be characterized as a cryptographic testimony to the fact that the blockchain maintained by the network is authentic. As producing the cryptography required for the testimony requires computational work, miners typically receive compensations for sacrificing electricity for the good of the network. These compensations are commonly referred to as *mining rewards* or *block rewards* (Dimitri, 2017; Böhme *et al.*, 2015).

Mining rewards are the most prominent form of revenue splitting in blockchain architectures. The rewards are issued by minting new cryptocurrency into the system at frequent intervals. This increases the total supply of tokens which—according to the quantity theory of money—reduces the value of each token respectively (see chapter 3.2.2.). Thus, the mining rewards somewhat resemble algorithmic *seigniorage*—an inflation tax collected from all platform participants and used to subsidize the production of public goods—namely distributed consensus and immutability of record (Athey *et al.*, 2016; Catalini & Gans, 2016).

Miners also typically receive another form of compensation for their efforts. When a user wishes to make a transaction through the platform, they can add a voluntary *transaction fee* to their request. As the miners are limited in their capacity to add transactions to the blockchain due to the fixed block-size and proof-of-work requirements, the transaction fees serve to ensure that the miners are incentivized to handle the transactions in an expedited manner. As most transactions have fees of some quantity attached to them by the users, the size of the transaction fee required for a normal throughput is determined by free-market competition between the transaction requests (Dimitri, 2017).

Unlike the miners, the platform developers and the nodes are not compensated for their platform provision functions through inflationary taxes and transaction tips (Filippi & Loveluck, 2016). Instead, in order to get compensated, they must rely on a third form of revenue splitting quintessential to blockchain platforms: *token investments*, as described in chapter 3.2.2.

4 Conclusions

In this paper, blockchain architectures were analyzed with the intent to determine whether they constitute multi-sided platforms. The paper also made an effort to delineate the internal governance structure of blockchain-enabled distributed platforms. This analysis was performed by applying Tiwana's (2014) framework on platform governance to the case examination of the Bitcoin cryptocurrency network.

On the basis of the case analysis of the Bitcoin cryptocurrency, blockchain architectures can clearly exhibit all the characteristics of a multi-sided platform, as outlined in the platform literature. The case architecture demonstrates direct network effects, as well as cross-side externalities. The interactions around the examined system can be described as multi-sided switch-role markets, and the technical and social boundary resources of these architectures are clearly defined.

Some discrepancies were observed, however, in regards to the wider perceptions of platforms in the platform literature. While blockchain-based distributed platforms coordinate and regulate the connections between its ecosystem participants (Gawer & Cusumano, 2002; Iansiti & Levien, 2004), they do not necessarily function as licensing authorities, as characterized by Rochet and Tirole (2004). To a certain degree, distributed platforms serve the role of a public interest regulator (Farrell & Katz, 2000), but do not exhibit the characteristics of a monopolist platform owner, as described by Boudreau & Hagiu (2008).

Several conclusions can be drawn from the case analysis in chapter 3.2. Firstly, in blockchain-enabled distributed platforms, not only have the product and service innovations pertaining to the platform been externalized, but the entire platform provision has been distributed across various market sides. In the examined case example of Bitcoin cryptocurrency, the distributed collaboration is held together by an intricate web of monetary incentives and different forms of interlocking control mechanisms exerted by the participating market sides towards one another.

Secondly, although Bitcoin is technically anarchistic in governance, some *de facto* structure exists to how the platform decision rights are allocated in Bitcoin. As no formal decision-making protocols are in place, an informal negotiation process takes place through various forms of indirect signaling.

Thirdly, blockchain-enabled distributed platforms seem to have introduced a new method of platform monetization. The contemporary platform business models have mainly been based on enabling direct interactions between the different market sides and monetizing by controlling access to those interactions and by leveraging information asymmetries. In blockchain-enabled distributed platforms, however, the linchpin business model seems to revolve around launching an independent, self-sustained open ecosystem of direct interactions, and monetizing on the tokens of value utilized as the means of exchange in that ecosystem.

Fourthly, much like contemporary multi-sided platforms, blockchain-enabled distributed platforms also seem to employ split revenue schemes, with two notable differences in regards to conventional multi-sided platforms. The first difference is that in Bitcoin, the revenue splits are not used to share profits between external complementary asset providers and the platform's owner, but between all the different market sides participating in the platform provision and the ecosystem at large. The second difference is that the platform pricing and the split revenue schemes are not monopolized by any single party but rather determined by the quasi-anarchistic, semi-structured decision-making process between the market sides, as well as free-market competition mechanics.

Boudreau and Hagiu (2008) have hypothesized that all the coordination problems related to the collaboration around multi-sided platforms cannot be solved through mere price-setting alone. In contemporary platforms, the economic incentivization only prevents market failures to the extent that the platform participants are compensated for their participation through revenue split models. In blockchain-enabled distributed platforms, however, the economic incentivization is more equilateral and ubiquitous than in contemporary platform models. Therefore, we argue that the variety of coordination problems and market failures that *can* be addressed through price setting is quite likely to be much wider in scope in distributed platforms (see Catalini & Gans, 2016).

Acknowledgements

This paper has been drafted as a part of the Work and Wealth in the Era of Digital Platforms (BRIE-ETLA) research collaboration of 2015–2018. Timo Seppälä has also received financial support for his work from the Blockchains Boosting Finnish Industry (BOND) research project.

Endnotes

1 For this chapter, we define blockchain technology as the cryptographically concatenated data structure and network architecture described by Nakamoto (2008) which entails a proof-of-work consensus protocol and employs cryptographic tokens of value, more commonly referred to as cryptocurrency.

2 In this chapter, we use the term platform in reference to a system that allow the various actors—users, providers and other stakeholders across organizational boundaries—to engage in value-adding activities. It is typical of platforms in this sense that the individual actors create, offer and maintain mutually complementary products and services for various distribution channels and multi-sided markets within the framework of common business and contract rules, governance and user experiences. A typical characteristic of a platform is to attract and lock in a range of actors keen to harness the economic benefits offered by direct and indirect network effects.

3 It should be noted that some similar types of categorizations have been drafted before in literature regarding Bitcoin's governance. For example, Filippi & Loveluck (2016) divides the governance of Bitcoin into two categories: "governance by the infrastructure" (i.e. the Bitcoin protocol managing the community) and "governance of the infrastructure" (i.e. the community managing the protocol). From the multi-sided platforms' perspective, the former bears great similarity to the concept of boundary resources (see. chapter 3.1.4.) and pricing policies (see chapter 3.2.3.), while the latter rather resembles the concept of platform decision rights (see chapter 3.2.1.). The categorizations are not directly interchangeable, however, as the control-category in Tiwana's framework (see chapter 3.2.2.) seems to incorporate aspects of both of Filippi's and Loveluck's categories simultaneously. Respectively, Gasser et al. (2015), speaks of "the power of influencing the normative content of the rules" and "their social realization" in Bitcoin. In this vernacular, the first half, again, relates to Tiwana's concept of decision rights, while the social realization somewhat equates to Tiwana's notion of control. However, in the context of platform literature, so far there has been little in the way of detailed conceptualizations of blockchain governance mechanisms.

4 It should also be acknowledged that many of the market sides specified in this paper contain several factions which are engaged in internal power struggles within the market sides. For example, developers have mostly organized themselves into rival developer communities, miners have diversified their risks by forming collective mining pools which compete against one another, and so on. (Böhme et al., 2015) However, the scope of this research does not permit us to delve deeper into these internal power struggles, as our main focus is on the power relations and the power mechanics between the different market sides.

5 For example, the first and most wide-spread blockchain platform to date, the Bitcoin network, uses native tokens called 'bitcoins', each divisible to 100 million 'satoshis'. The source code of the system is set up in such a way that minting new bitcoins becomes exponentially more difficult as time passes on. This way, the maximum number of bitcoins that can exist in the system is limited to 21 million by the current consensus protocol.

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Article 4

Expanding the Platform: Smart Contracts as Boundary Resources

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Original publication:

Lauslahti *et al.* (2018). Expanding the Platform: Smart Contracts as Boundary Resources. In: Smedlund A., Lindblom A., Mitronen L. (eds) Collaborative Value Co-creation in the Platform Economy. Translational Systems Sciences, Vol 11. Springer, Singapore.

Abstract

Platform businesses are born global, with instant access to global markets. Thanks to the algorithmic, self-executing and self-enforcing computer programs known as smart contracts, platform businesses now also have instant access to global capital markets from birth. However, the legal status of these smart-contract-enabled funding mechanisms and smart contracts in general is not well defined. In this article, we analyze how well the formation mechanisms of the general principles of Finnish contract law can be applied to the technological framework of smart contracts. We find that depending on the case, smart contracts can create legally binding rights and obligations to their parties. We also observe that contracts have not been formerly perceived as technical boundary resources in the sense that platform ecosystems could foster broader network effects by opening their application contracting interfaces to third parties.

Keywords

platform, smart contract, boundary resource, contract law, ICO

1 From digital contracts to lex cryptographia

In 1994, American cryptographer Nick Szabo published an article in which he outlined the concept of smart contracts[1]. Szabo defined smart contracts as machine-readable transaction protocols which create a contract with pre-determined terms[2]. In its simplest form, a smart contract is a machine-readable program, written in code that will execute itself when a set of pre-determined terms are met.[3]

Regardless of the advanced ideas and the advanced concept, the IT infrastructures of the era were considerably behind the level required to bring Szabo's vision to reality, and the time was not yet ripe for practical experimentation (see *e.g.* Glatz, 2014). Now years later, the concept of smart contracts has resurfaced as the technological development has caught up with the vision (see *e.g.* Marino, 2016). New technical advances in blockchain technology[4] have enabled the transition from automated digital contracts to truly autonomous smart contracts, capable of self-execution and self-enforcement.

The relationship between platforms[5], blockchain-based smart contracts, and contract law creates an interesting research environment in which the traditional definition of contracts is placed under review as coded programs begin to administer transactions. Moreover, legal research on blockchain technology has been said to lead to the development of a new legal field which can be described as *lex cryptographia*, or crypto law[6]. Determining the legal nature of smart contracts is in fact a key theme in the surrounding discussion[7] in which they have been increasingly assessed as legally relevant activity[8]. Thus, it should be noted that smart contracts are not only administered by their programming logic or, in other words, the code they contain; they are also inseparably influenced by the state of the law[9].

Platform businesses are born global, with instant access to global markets. Through recent developments in smart contracts, platform businesses now also have instant access to global capital markets from birth[10]. However, the legal status of these smart-contract-enabled funding rounds and smart contracts in general is not well defined at this point. The techno-economic point of view has traditionally been selected as the dominant way for understanding technological disruptions and their effects. In recent years, however, legal regulation has also been increasingly understood as an equally important factor in developing innovations in the platform economy (see Chander, 2014). This calls for a systematic review of the legal doctrinal composition of smart contracts within the context of an established legal framework.

Frameworks of the same historic background—such as those with their roots in the Romano-Germanic legal tradition—share more commonalities with each other than with systems descending from another historic background—such as those based on the common law legal tradition. Therefore, there are differences in the compositions of contractual mechanisms is different legal frameworks. Thus, an all-pervasive systematic review cannot be covered in one research article. Instead, the legal doctrinal composition of smart contracts must be evaluated for each legal framework individually.[11]

In this chapter, we examine the relationship between blockchain-based smart contracts and Finnish contract law.[12] The main research question herein is *whether or not legal acts can be concluded with smart contracts under Finnish contract law*.[13] In order to provide an answer, it must, first of all, be clarified how the general doctrines of contract law are applicable to these new smart contracts in terms of conferring rights and imposing obligations on parties. Secondly, it must be determined whether all smart contracts constitute contracts in themselves, or whether there are internal requirements for their legal significance.[14]

We conclude the chapter with a discussion on the implications of our findings on multi-sided platforms and the platform economy at large. Smart contracts are a clear example of how some social boundary resources of platforms are developing in an increasingly technical direction, and should be perceived as technical enablers, similarly to technical boundary resources[15]. Contracts in themselves have not been formerly perceived this way, in the sense that the network effects of a platform ecosystem could be boosted by opening up "application contracting interfaces". This would mean, for instance, the application of even further automated digital contracting mechanisms, process automation that reaches further beyond a company's own information systems, as well as further automated and more dynamic networks of contracting parties.

This chapter continues as follows: In the second section of the chapter, we will outline the definition of smart contracts and discuss the creation of a smart contract from the perspective of contract law. In section three, we will seek to answer the question of whether legal acts can be concluded with smart contracts, and finally, in section four, we will discuss the impact of smart contracts in the context of development trends of digital platforms and the surrounding ecosystems.

2 The nature of smart contracts

2.1 Smart contracts

A fully established definition for smart contracts has yet to be formed. According to Nick Szabo, creator of the concept behind smart contracts, however, the most primitive example of a smart contract is, in fact, a regular vending machine where transactions are based on simple mechanical automation. The vending machine, due to its physical design, accepts coins, hands over the selected item, and finally returns the change. The machine, therefore, completes the transaction on its own when the necessary prerequisites are met—that is, a sufficient amount of money has been deposited into its slot. Anyone in possession of a sufficient amount of coins and with the desire to purchase one of the items for sale is capable of becoming a contracting party in this type of a transaction. Additionally, since the items for sale are situated within the vending machine, it is capable of protecting the logic of its proposed contract from unauthorised changes (Szabo, 1994).

Much in the same way as vending machines, digital smart contracts can essentially be characterized as cryptographic "boxes" containing value that only unlocks upon the fulfilment of the preconditions determined in their design (Ethereum White Paper, 2013). In other words, smart contracts are automated mechanisms under the control of which assets can be deposited, and which then autonomously redistribute those assets according to their internal programming logic.[16] As such, smart contracts enable the execution of transactions to be automatically based on data that was not yet available when the contract itself was concluded (Buterin, 2014).

Diverging from contracts concluded in the form of action, speech or writing, a smart contract is characteristically a computer program built in code. Moreover, as currently employed in reality, smart contracts are based on decentralized peer-to-peer networks, and reside in a distributed network database known as a blockchain.[17] In order to implement a contractual arrangement as a smart contract in practice, the terms of the proposed contract are formulated in programming language, after which the smart contract is deployed in the blockchain. Once deployed, the distributed blockchain network executes the smart contract automatically without the assistance of the contracting parties whenever the conditions outlined in the code of the smart contract are met.

Due to their decentralized nature, smart contracts are often said to be *self-executing* and *self-enforcing*. In other words, they differ significantly from conventional forms of digital contracts, such as click-wrap contracts, in that they do not require a centralized trusted party to administer the execution of the contract in the digital world.[18] Moreover, blockchain networks are capable of preventing unauthorized changes to the internal logic of the smart contracts in their distributed database. Therefore, no party or authority has the power to prevent such networks from executing the smart contracts in their original form (Mattila, 2016, p. 15).[19]

Based on all the characterizations above, we define smart contracts for this chapter as digital programs that:

a) are written in computer code and formulated using programming languages,
b) are stored, executed and enforced by a distributed blockchain network
c) can receive, store, and transfer digital assets of value, and
d) can execute with varying outcomes according to their specified internal logic.

From this definition, it is easy to see that the established term for describing such cryptographic boxes of value, namely "smart contracts", can be quite misleading, as their smartness as well as their contractual nature can both be called into question. In essence, smart contracts are merely automatic programs built in code and deployed on a blockchain to perform logical processes. Thus, the term "smart contracts" is also commonly used in connection with many other types of programs situated in the blockchain and not only those resembling a formal agreement (see *e.g.* Stark, 2016). Smart contracts are also capable of actions such as collecting data from outside resources (API oracles) and processing it according to the terms specified in their programming logic, and executing concrete varying outcomes based on the results of this procedure (BBVA Research, 2015).

Nonetheless, it is possible to give smart contracts characteristics that can be likened to those of conventional contracts—at least from a theoretical viewpoint—by formulating their internal logic accordingly.[20] In such cases, smart contracts begin to show contract-like characteristics once digital assets have been transferred to their control, and once they are transferred again in order to redistribute them according to the pre-specified criteria.[21]

2.2 Contract law and the interpretation of smart contracts

Contracts are a key legal instrument for private operators as they execute changes in their legal relations or try to prepare for future turns of events. Contracts also enable organised collaborative activity and are often used to carry out economic activity (Hemmo, 2003, p. 4; 2006, p. 27). The definition of the term "contract" contains a number of different meanings. First of all, the term may refer to the conclusion of the agreement itself, therefore describing the parties' commitment to the contract. Secondly, it may refer to the contents of the agreement, therefore determining the parties' rights and obligations in relation to one another. Thirdly, it may refer to the actual document in which the terms of the contract have been specified (Saarnilehto et al., 2012, p. 310).

Contract law is traditionally non-mandatory. In other words the parties can disregard certain rules of presumption by implementing their own terms. This principle of freedom of contract is the premise from which Finnish contract law also sets out. For a number of reasons, however, freedom of contract is restricted by certain mandatory rules regarding the content of agreements (Hemmo, 2003, p. 77). The main principle is, nonetheless, that parties can exercise full freedom in deciding whether to enter into a contract, with whom, in what manner, and with what terms. The right to decide on the dissolution of a contract has also been considered an important, yet separate, part of freedom of contract (Hemmo, 2003, p. 69–77).

In addition to the principle of freedom of contract, the Finnish legal system also acknowledges the principle of *pacta sunt servanda*; that is, agreements must be kept.[22] Various sanction mechanisms also make it necessary to abide by the contracts one has entered into, since the other party has the opportunity to claim damages or enforce the contract by help of the authorities (Hemmo, 2003, p. 14; Saarnilehto, 2009, p. 161–163).

In this publication, we will address contracts as individual agreements concluded between rational and equal private parties with the main purpose of organising economic legal relations. Due to practical reasons, our presentation of Finnish contract law will be limited to a rather general level, focusing on the mechanisms leading to the conclusion of a contract. Our goal in this endeavour is to analyse through doctrinal research[23] and as straightforwardly as possible those aspects of contract law which are relevant to the interpretation of smart contracts. This perspective leaves out several significant legal themes which we are not able to explore in this publication. Since there has been little research on smart contracts, this type of approach is necessary in order to define them and assess them in a legal context.

2.3 Legal acts, declarations of intent and contracts

The relationship between legal acts and contracts has so far been widely discussed in Finnish legal literature, and scholars have tried to find differences in the meanings of these terms. Recently, however, these terms have increasingly often been used as synonyms for each other[24], although Finnish legislation still includes well established expressions which utilise the term legal acts. In this publication, we will adhere to the practice of using the two terms synonymously.

Consent, declaration of intent and the purpose that this intent becomes known to the other party have all been considered *sine qua non* for a legal act. Consent refers to a party's free will to become bound by the contract. In addition, this consent must become known to the recipient in one way or another (Saarnilehto *et al.*, 2012, p 323). Declaration of intent refers to the expression of a party's[25] free will as a prerequisite to the conclusion of a contract. Both parties are free to decide what their will is and how they are bound to the decision. Although the declaration of intent should by principle be directly addressed to a certain other person or group, even a declaration of intent addressed to a more vaguely specified person or group of people can be seen as valid (Saarnilehto *et al.*, 2012, p. 323). This, however, requires a restriction of some sort regarding the targeted group, as entirely unspecified public declarations of intent have by principle been considered non-binding. The reasonable impression that the declaration has had on the recipient has been utilised as a key argument in assessing whether or not the declaration has binding effects. For instance, an advertisement in a newspaper has not as such been considered a sufficient offer (Hemmo, 2006, p. 78–79). On the other hand, an automat which has been set up with its for-sale items and relevant information (regarding prices, methods of payment, products, etc) may be considered a de facto offer which has been made to a sufficiently limited audience, that is, those in the immediate vicinity of the automat.

The declaration of intent must be expressed clearly. That said, an implied expression of intent is also valid, and intent can be expressed through various forms of communication. The thought or idea of an agreement alone, however, does not constitute a declaration of intent. The method, form and audience of the declaration are not subject to overly strict regulation, and it is in fact sufficient that consent is expressed in one way or another (Saarnilehto *et al.*, 2012, p. 328). It is also not imperative to apply an overly strong presumption on the necessity of such a declaration. Not all methods of concluding a contract even require a proper declaration of intent. Additionally, the declaration of intent does not need to be entirely separate from the agreement, as a contract can also be concluded based on passivity or concrete actions (Hemmo, 2003, p. 11–13). It follows that a party's true will to be bound and some expression of this intent are of key importance.

A contract is a bilateral legal act which establishes rights and obligations for the parties to it. Only the parties to a contract may demand that these obligations should be met. A third party only has this right in certain exceptions (Norros, 2007, p. 1–3). In Finnish jurisprudence, contracts have traditionally been defined as the combination or amalgamation of two or more legal acts requiring one another. In some cases, specific requirements as to form must also be met or certain actions must be performed before a contract can fully enter into force (Saarnilehto, 2009, p. 3; Saarnilehto *et al.*, 2012, p. 367–368). The conclusion of a contract is often related to the organisation of economic activity[26]. In recent decades, however, the social dimension of contracts has also been emphasised. A reasonable balance in terms of the material content of a contract has been considered a prerequisite for the binding effect of a contract. In addition, parties in a weaker position are not thought to have a very extensive duty to investigate or make enquiries.[27]

2.4 Mechanisms for concluding contracts

The so-called offer–acceptance mechanism, as it is regulated in the Finnish Contracts Act, is seen as the traditional method for concluding a contract and is based on two legal acts. As contracts are becoming all the more diverse, the offer–acceptance mechanism is not, however, always the most accurate description of the process leading to the conclusion of a contract (Hemmo, 2003, p. 96–97). Under section 1 of the Contracts Act, the offer to conclude a contract and the acceptance of such an offer are binding in regard to the offeror and the acceptor. The Contracts Act, however, does not apply to contracts of standard form or contracts which require acting upon in order to become effective.[28] The response to the offer must be delivered on time and must accept the original offer as such. The Contracts Act provides that a response that purports to be an acceptance, but includes additions or restrictions, is to be deemed a rejection constituting a new offer directed at the original offeror.[29]

Mechanisms for concluding a contract not regulated by the Contracts Act include contracts concluded through negotiation, implied contracts and tacit agreements. Standard form contracts are also considered to be formed outside the offer–acceptance mechanism (Hemmo, 2003, p. 129–137). Aside from contracts concluded via the offer–acceptance mechanism, implied contracts and tacit agreements are the most relevant to smart contracts. In addition, smart contracts may contain similar characteristics to contracts requiring acting upon in order to become effective.

Implied contracts refer to a situation where a contract is seen to have been concluded without explicit expressions of intent, but rather based on social norms. In these situations a contract has been concluded based on some action, without any oral or written exchanges. Typically these actions have similar qualities to a contract and are part of a prevalent social convention which both parties are deliberately participating in (Hemmo, 2003, p. 131–133). Examples offered by legal literature of such social conventions could be using public transportation or parking in a paid parking lot. Using an automat has also sometimes been placed in this category. In summary, implied contracts are contracts based on certain facts inducing a contractual relationship but where no explicit offer–acceptance mechanism takes place.

The term "tacit agreements" is also used to describe a slightly similar phenomenon. The term refers to the conclusion of a contract through a situation in which no explicit declaration of intent can be detected, although the parties collaborate in a way that indicates the existence of a contractual relationship (Hemmo, 2006, p. 88). It has been stated in legal literature that it is mostly a matter of taste which term to use[30] (Saarnilehto *et al.*, 2012, p. 385). When parties collaborate in a way that denotes a contractual relationship, a contract is seen to have been implicitly concluded, even though the method and time of conclusion and the contract itself cannot be shown. Therefore, if parties have commenced action as if the contract were in force, despite the contract's itself remaining in the stage of negotiations or not yet having being concluded, an implicit contract may be in force between the parties. The interpretation of whether a tacit agreement has been concluded is based on overall evaluation, in which circumstances strongly speaking in favour of the existence of a contract can prove that a tacit agreement has entered into force. However, even rather minor arguments against the existence of a contract can relatively quickly lead to the conclusion that no tacit agreement has been reached between the parties (Hemmo, 2003, p. 133–136). Interpretation should not be too liberal in order to avoid parties being bound to contracts they have not declared their intent for (Hemmo, 2006, p. 88).

According to legal literature, a declaration of intent leading to the conclusion of a contract can be expressed by the parties through the exchange of assets or services with one another. A similar transaction-based interpretation has also been outlined in regard to smart contracts (Koulu, 2016, p. 65). A declaration of intent by acting upon it can, for instance, take place in the purchase of items from a vending machine. In this case, the proprietor selling items and services via the vending machine has implicitly displayed its desire to conclude a contract with the terms specified by the vending machine. This is supported, for example, by the fact that the proprietor has first had to obtain the vending machine and a location for it, set up the vending machine and fill it with products, program the vending machine and make it operational before any contracts can be concluded. The user also expresses their will to be bound to the transaction similarly via the vending machine. The vending machine example can also be described using the offer–acceptance mechanism; however, tacit agreements seem more relatable to the reality of the phenomenon (Saarnilehto *et al.*, 2012, p. 384–385).

The Supreme Court of Finland has stated in case KKO 2010:23 regarding private parking enforcement that the offer–acceptance mechanism of the Contracts Act no longer corresponds with all situations related to the conclusion of a contract. Contracts concluded via automats were mentioned in the ruling as another relevant example of these types of contracts.[31] The conclusion of a contract can therefore also be attributed to external characteristics presented in the parties' actions (Saarnilehto *et al.*, 2012, p. 384–385).

2.5 Conclusion of a smart contract

In the previous section, we presented a number of mechanisms for concluding a contract. In this section, we will be comparing these mechanisms and evaluating how well contract law doctrines regarding the conclusion of contracts are applicable to smart contracts.[32]

Especially in the offer–acceptance mechanism of the Contracts Act, the parties' declarations of intent are explicit, in other words the acceptor is given the details of the offer and the offeror is given information on the response. On the other hand, as explained previously, consent can be expressed implicitly, for instance through co-operation with the other party or the performance of duties. Since the doctrine on declaration of intent holds a strong principal position in the Finnish legal system, this must also be taken into account when discussing the conclusion of a contract from the perspective of smart contracts.

In reference to what has been discussed previously, it appears possible that smart contracts can be concluded based on the parties' declaration of intent. Although it seems that the offer–acceptance mechanism can be applied to smart contracts, their conclusion seems to be better explained by the processes leading to tacit agreements and implied contracts. In the context of the offer–acceptance mechanism, the parties would come to a binding agreement via the offer of one party and the acceptance of the other. Only thereafter are transactions or other actions performed in accordance with the contract. With smart contracts, the intent of the party responsible for placing the smart contract in the blockchain seems to manifest in the same context where a contracting party transfers a certain digital asset to be managed by the smart contract.[33] Declaration of intent does not therefore appear to occur separately from the conclusion or execution of a smart contract, but is rather an immovable part of the contract itself.[34] Then again, if observed in light of the offer–acceptance mechanism, a public smart contract added to the blockchain to which the party has transferred assets for management may perhaps be interpreted as an offer[35]. Respectively, another party's joining the smart contract may be seen as acceptance of the offer[36].

The expressions of intent in the conclusion of a smart contract share many characteristics with a tacit agreement, where the contract is concluded by parties exchanging assets. When a party transfers the sum into the smart contract, and the other party begins to act based on the smart contract, the expressions of intent of both parties are included in the actions taken. Even though no deliberate expressions of intent are given, the actions of the other party are required in order to be bound to the contract[37]. A parallel can be drawn between this situation and the previously mentioned situation involving an automat. This interpretation is enforced partly by the fact that Szabo has mentioned in some of the first publications about smart contracts that an automat is the simplest form of a smart contract.[38]

Based on aforementioned details, acts performed by the parties of a smart contract can likely be thought to fulfil the definition of declaration of intent.[39] Therefore, at least certain types of smart contracts can feasibly be concluded either by acting upon them or implicitly, as demonstrated in the aforementioned vending machine example. Here the "creator" of the smart contract announces their will to conclude contracts by building a smart contract in the blockchain and transferring, for example, certain assets to it. The other party of the smart contract expresses their will to be bound by performing an act in accordance with the terms of the contract, therefore accepting the offer without a distinct and explicit declaration of intent. Finally, when the preconditions specified in the smart contract are met, it executes itself automatically and for example redistributes the digital assets placed under its management or performs other tasks it has been appointed with, following which the contract can be thought to have been expired.[40]

However, not all smart contracts are as simple in reality. Next, we will discuss examples of different types of smart contracts and aim to highlight their various characteristics.

3 Can smart contracts be used to perform legal acts?

3.1 Case: API oracle

The first example is about so-called oracles, in other words routers connecting a set of application programming interfaces (APIs). This type of smart contract collects data from one or more third-party software interfaces or other sources, and relays the collected information into the blockchain.

The main purpose of oracles is to provide information to other smart contracts in order to monitor the fulfilment of the terms of the contract. This is to ensure that one of the basic requirements of a functional consensus architecture is met: each party must be able to check the validity of the information in the blockchain. If the smart contracts were to monitor the fulfilment of the terms of the contract via information available on typical websites or third-party software interfaces then the risk would be that each party would find different results, thereby undermining the reliability of the contracts. Hence all factors which will affect the smart contracts must be brought into the blockchain through oracles.

Quite understandably, there are some trust issues related to using individual oracles, where one wants to maintain the benefits of using decentralised consensus architecture. In its simplest form, however, a smart contract functioning as an oracle would appear as follows:

Smart contract (Solidity code)

```
pragma solidity ^0.4.11;

contract Oracle {

  address oracle;
  uint[] public data;

  function Oracle() {
    oracle = msg.sender;
  }

  function reportData(uint newData)
  {
    require(msg.sender == oracle);
    data.push(newData);
  }
}
```

Obviously the oracle in itself does not resemble what is commonly understood in our contract law as a contract. The example given above contains no typical features of a contract. In addition, the smart contract does not include identifiable parties and therefore does not include anyone's expression of intent. Its only purpose is to collect data from one location and send it to another. This type of a smart contract functions specifically as a program designed to relay data. This example quite clearly illustrates the problems caused by the discrepancies between the terminology and contents of smart contracts. Even though the entirety of the contracts which the oracle is a part of may resemble a typical contract, the oracle in itself would still be nothing more than a program designed to relay data.

3.2 Case: Search engine optimisation

A slightly different example of a smart contract is a basic service level agreement. This type of contract could, for example, be used to estimate the success of search engine optimisation. In this scenario, a buyer looking to purchase search engine optimisation services has created a smart contract into a blockchain, specifying the optimisation services required. The buyer will deposit the offered amount of value into the contract. A seller who wishes to enter into the agreement does so by also depositing an amount of value into the contract as collateral. Once the deadline specified in the terms of the smart contract is due, the contract will assess whether the buyer's domain is amongst the top three Google search results for the search term "example", conducted by a specified oracle. If the terms of the contract are met at the time of the deadline, the seller will receive both of the deposited sums. Conversely, if the terms are not met, both of the deposits will go to the buyer. The described smart contract could be written as follows:

Smart contract (Solidity code)

```
pragma solidity ^0.4.11;

contract GoogleSearchOracle {
  function getRanking(string url, string searchTerm) constant returns (uint);
}

contract ServiceLevelAgreement {

  GoogleSearchOracle oracle =
  GoogleSearchOracle(0x8b2087984b3b3f15450a644887f100d9559bb0cc);

  address buyer;
  address seller;

  uint price = 190 ether;
  uint collateral = 2 ether;
```

```
    uint maxAcceptedRank = 3;
    string domainName = "http://www.example.com/";
    string searchTerm = "example";
    // 2017-10-15 at 0 hours 0 minutes 0 seconds in Unix time
    uint deadline = 1508025600;

    function ServiceLevelAgreement() payable {
      require(msg.value == price);

      buyer = msg.sender;
    }

    // The contract can be canceled as long as it hasn't been accepted by anyone
    function cancel() {
      require(msg.sender == buyer);
      require(!seller);

      selfdestruct(buyer);
    }

    function accept() payable {
      require(!seller);
      require(msg.value == collateral);

      seller = msg.sender;
    }

    function doSettlement() {
      require(seller);
      require(now >= deadline);

      // By default, send the deposit to the seller of the service...
      address recipient = seller;
      // ...but, if failed to reach the agreed service level, return the deposit to the buyer
      if (oracle.getRanking(domainName, searchTerm) > maxAcceptedRank) {
        recipient = buyer;
      }

      if (!recipient.send(price + collateral)) {
        throw;
      }
    }
  }
```

In this example, the buyer has drafted a contract-like digital instrument and deployed it in a public blockchain. This act can be interpreted as an indication of the buyer's willingness to enter into an agreement. The seller demonstrates the same willingness to enter into an agreement by depositing the pre-determined sum of value into the contract. Such a construction is very similar to a tacit agreement, and is therefore quite a clear example of how legal acts can be performed with smart contracts.

It is noteworthy, however, that although the smart contract in this example allows the contracting parties to align their incentives in such a way as to achieve their contractual goals, technically the arrangement itself does not involve any contractual obligations for the seller to optimize the search engine results. Essentially the contract constitutes a simple bet on the search result placement of a certain domain on a given date, at a given time. It simply then follows from this bet that the passivity of the seller in this respect would result in the loss of the seller's own deposit and the forfeiting of the buyer's deposit.[41]

Based on this example, when evaluating the legal position of smart contracts and the obligations and rights which they create for the parties involved, it bears significance how and between which parties the smart contract was created.[42] In light of our current legislation dealing with contract law, the casuistic nature of the evaluation is emphasised.

3.3 Case: Token sale (a.k.a. initial coin offering, ICO)

Smart contracts can also be used for purchasing shares in so called *token sales*, or *initial coin offerings* (*ICO*). The idea herein is somewhat analogous to crowd-funding applied to pre-seed venture capital funding rounds for start-ups. As funds are paid into the smart contract, tokens are transferred to the purchasing party to represent the ownership of shares. These tokens can be programmed to include several types of functionality, including dividends, voting rights, and access to goods and services later on produced by the company.[43]

In this example, in order to raise funds for a start-up company, an issuer is offering to sell share-representing tokens for a predetermined price of 1 ether per token, and offers to accept all purchases conducted before the set deadline. The smart contract could be drafted as follows:

Smart contract (Solidity code)

```
pragma solidity ^0.4.11;

contract ICO {

  address tokenIssuer;
  uint collectedEther;
  uint minFunding = 2500 ether;
  mapping (address => uint) public balances;
  // 2017-10-15 at 0 hours 0 minutes 0 seconds in Unix time
  uint icoDeadline = 1508025600;

  function ICO() {
    tokenIssuer = msg.sender;
  }

  function mint() payable {
    require(now < icoDeadline);
```

```
    collectedEther += msg.value;
    balances[msg.sender] += msg.value;
  }

  function transfer(address receiver, uint amount) {
    require(fundingSuccessful());
    require(balances[msg.sender] >= amount)

    balances[msg.sender] -= amount;
    balances[receiver] += amount;
  }

  // If funding was successful, the token issuer may withdraw all deposits
  function withdrawFunding() {
    require(fundingSuccessful());

    if (!tokenIssuer.send(collectedEther)) {
      throw;
    }
  }

  // If funding failed, investors may withdraw their investments back
  function withdrawInvestment() {
    require(now >= icoDeadline && collectedEther < minFunding);

    uint investment = balances[msg.sender];
    balances[msg.sender] = 0;

    if (!msg.sender.send(investment)) {
      throw;
    }
  }

  function fundingSuccessful() private constant returns (bool) {
    if (now >= icoDeadline && collectedEther >= minFunding) {
      return true;
    }
    return false;
  }

  function payDividends() {
    ...
  }

  function vote() {
    ...
  }
}
```

In this case, the issuer of the token sale has drafted a smart contract and publicly deployed it, specifying the offered price, the minimum funding threshold, and the termination deadline of the offer. Investors wanting to engage in an investment arrangement with the issuer can do so by transferring their stake as cryptocurrency tokens into the smart contract. Once the termination deadline has been reached and the offer has expired, the smart contract will determine whether a sufficient amount of funds has been committed to the funding round. If the minimum threshold has been surpassed, the contract will release the funds transferred into the contract to the issuer of the token sale, and the funders will be issued share-representing tokens accordingly.

In this example, the expressions of intent of the parties are quite clear, and the contract can be seen to have been concluded tacitly. The issuer's expression of intent (offer) is manifested in the act of deploying the smart contract into a blockchain, and the funder's reciprocal acceptance takes form in the depositing of the funds into the smart contract. The situation can therefore be interpreted via the offer–acceptance mechanism found in the Finnish Contracts Act such that the issuer has shown their willingness to enter into the contract by placing the smart contract into a blockchain, and the funder has reciprocated by transferring the funds. If the offer has been sufficiently identifiable then this interpretation is viable. The third example seems to reinforce the understanding that a smart contract can be a contract in the typical legal sense of the word, if an offer–acceptance mechanism can be sufficiently identified. This view is further reinforced when the example is interpreted analogously in comparison with the vending machine example.[44]

4 Conclusions and discussion

Smart contracts can be drafted on very different bases and for entirely dissimilar purposes—not all of which meet the characteristics and the legal requirements of a contract. Based on the empirics in section three, however, it seems rather clear that legal acts *can* be concluded in the form of smart contracts. In this regard, the manifestation of intent through the exchange of performances appears to be of focal importance. A similar mechanism has been previously presented in the Finnish legal literature—namely, the vending machine, where the implicit nature of declarations of intent is highlighted in the formation of the contract. However, due to the fact that smart contracts are not specifically covered in the current legislation, legal ambiguity may arise as a consequence of their conceptual unconventionality.[45]

In addition to the ambiguity in regards to the letter of the law, smart contracts can also be subject to algorithmic ambiguity, so to speak. When co-operation is organised just by the programming code of a smart contract, trying to understand the true legal content of the arrangement on the basis of the programming code alone can be problematic.[46] Although this chapter has described three examples of smart contracts, in reality the number and the scope of possible applications may be practically infinite. The variety of smart contracts may cause various legal issues, the effects of which may be hard to anticipate at such an early stage[47].

With the focus on such potential challenges, "soft law" arrangements, such as so-called dual integration systems[48] and systems based on various model agreements[49], have already been developed to help prove the existence of a contract in the legal domain.[50] It is thus likely that smart contracts will first and foremost be utilised in the context of standard-form contracts and other kinds of simple contracts that do not involve ambiguous legal terms. Nevertheless, engaging in discussions about developing the legal doctrinal composition of smart contracts, both on the national as well as the European Union level, should be considered an equally important and topical approach in the matter.

In the literature on platform economy, boundary resources have traditionally been understood as technical tools used to lower the threshold for third parties to join part of a company's platform ecosystem. The perspective of technical tools, however, has yet to be applied to social boundary resources on a similar scale. Smart contracts are a clear example of how social boundary resources are developing in an increasingly technical direction. It is becoming increasingly difficult to draw a distinction between technical and social boundary resources of platforms. Social boundary resources should therefore be perceived as technical enablers, similarly to technical boundary resources (*cf.* Gawer, 2009; Ghazawneh, 2012; Ghazawneh & Henfridsson, 2013).

Contracts in themselves have also not been formerly perceived as boundary resources, in the sense that the network effects of a platform ecosystem could be boosted by opening up so-called *application contracting interfaces, ACIs* (*cf. application programming interfaces, APIs*). This would enable the creation of more highly automated digital contracting mechanisms, process automation that reaches further beyond companies' own information systems, as well as more automated and more dynamic networks of contracting parties.

In general, smart contracts can be expected to disrupt the development of the platform economy by enabling unprecedented ways to co-operate in open platform ecosystems. As for managerial implications, companies should address the following three considerations:

1) How can smart contracts be used to lower the threshold for third parties to enter the company's platform ecosystem, in the same manner as technical boundary resources have been used for opening interfaces and offering ready-to-go tools for development?
2) In cases where companies have several contracting interfaces towards their clients, suppliers and, other interest groups, which interfaces are suitable for the use of smart contracts with each respective party?
3) If several parties are subjected to the same smart contract in a vending-machine-like manner, are contractual arrangements required by successful business strategy becoming more fragmented, if individual deliveries are comprised of several constituent parts of separate suppliers?

Acknowledgements

This paper has been drafted as a part of the Work and Wealth in the Era of Digital Platforms (BRIE-ETLA) research collaboration of 2015–2018. Timo Seppälä has also received financial support for his work from the Integrating Platform Competences toward Network Effects (iPlate) research project.

Endnotes

1 The original text '*Smart Contracts*' is available at: http://szabo.best.vwh.net/smart.contracts.html (17 June 2016). The text "*The Idea of Smart Contracts*" published in 1997 took the idea of smart contracts further: http://szabo.best.vwh.net/smart_ contracts_idea.html (17 June 2016).

2 By transaction protocols Szabo meant protocols between different devices, which achieve the so-called Nakamoto consensus. Szabo, 1994: "*A smart contract is a computerized transaction protocol that executes the terms of a contract*". According to a newer definition, a smart contract is "*a set of promises, specified in digital form, including protocols within which the parties perform on these promises*". (Szabo, 1996).

3 It is noteworthy that smart contracts do not need artificial intelligence to work, regardless of what their name may suggest.

4 For this chapter, we define blockchain technology as the cryptographically concatenated data structure and the network architecture described by Nakamoto (2008) which entails a proof-of-work consensus protocol and employs cryptographic tokens of value, more commonly referred to as cryptocurrency.

5 For this chapter, we define a platform as an IT system that enables a multi-sided market environment where different market sides can perform value-adding activities that are complementary to one another, and which are governed by boundary resources. For further platform literature, see *e.g.* Cusumano & Yoffie (1998); Cusumano & Gawer (2002), Cusumano (2005, 2010); Parker & van Alstyne (2005); Eisenmann *et al.* (2006); Gawer & Henderson (2007); Boudreau & Hagiu (2008); Gawer & Cusumano (2008); Gawer (2009); Baldwin & Woodard (2009); Tiwana (2010); Yoo *et al.* (2010); Kenney & Pon (2011); Parker & Van Alstyne (2014); Hagiu (2014); Pon *et al.* (2014, 2015); and Parker *et al.* (2016).

6 A new legal field '*Lex Cryptographia*' focuses on rules which are managed through self-executing smart contracts and decentralised autonomous organisations. See Wright & De Filippi (2015, p. 48).

7 About the nature of smart contracts more generally: "*They are defined variously as 'autonomous machines', 'contracts between parties stored on a blockchain' or 'any computation that takes place on a blockchain'. Many debates about the nature of smart contracts are really just contests between competing terminology* [...]", http://www.coindesk.com/making-sense-smart-contracts/ (23 August 2016).

8 Glatz, (2014): "*It is however undeniable, that smart contracts have to be classified as legally relevant behavior.* [...]" (see also Koulu, 2016, p. 54).

9 See eg: *Blockchain 2.0, smart contracts and challenges*: http://www.twobirds.com/en/news/articles/2016/uk/blockchain- 2-0--smart-contracts-and-challenges#1 (23 August 2016).

10 Global capital markets have been enabled by a phenomenon around blockchain technology generally referred to as *token sales* or *initial coin offerings* (*ICO*). For more information on ICOs, see *e.g.* Conley, (2017).

11 It is noteworthy that the legislation concerning electronic contracts and information society in general has been harmonized to an extent on the EU level (*e.g.* in Finland's case, see the Finnish Information Society Code, 917/2014). In the case of characterizing the legal status of a single service provider utilizing smart contracts, a more systematic review on the EU level could be in order. However, as this chapter focuses on answering a more basic question about the contractual applicability of smart contracts in general, this harmonized legislation does not fall within the scope of this research. Similarly, on the national level, other mandatory provisions (*e.g.* distance selling and distance selling of financial services) may have legal implications concerning smart contracts. These include *inter alia* the conclusion of special consumer contracts and other public-law-oriented provisions in acts such

as the Money Collection Act (255/2006), the Crowdfunding Act (734/2016), and the Securities Markets Act (746/2012).

12 Due to the notable proximity of the Finnish legal framework to those of the other Nordic countries, some analogies thereto most likely are justified.

13 In this chapter, the research method of choice is mainly legal doctrinal (or legal-dogmatic) research, the main focus being on the research of current positive law—but in our case, examined in a broader context of the platform economy (see Hirvonen, 2011, p. 21–23, 28–30).

14 In this publication, it is not possible to discuss central guidelines not related to the content of smart contracts or the interpretation of such content. Questions regarding parties and legal entities in general have also been left undiscussed apart from a few mentions. Furthermore, the question of which country's national legislation should be applied to smart contracts is also interesting. Smart contracts exist in a blockchain that functions in a decentralised environment, and the parties (of which there may be several) may be completely unknown to one another. Therefore, it may not be clear which jurisdictions are relevant to the contract unless specifically referred to in its terms. It is important to study this question, but it is likely that any factual solutions to this issue will only be found through practice. In addition to the questions above, it is also important to consider how programming is viewed by Finnish contract law. Is it possible to equate the programming of a smart contract to a middleman, comparable to counsel drafting a traditional contract? While these interesting questions are mostly brushed aside in this text, it should be noted that the importance and role of programming will be an increasingly important topic in the future.

15 In platform literature, boundary resources are the operational regulations and technical tools and interfaces governing the interaction between the platform owner and the platform participants. They can be used either to encourage platform development or to restrict it in places where the platform owner wishes to maintain control over the developmental direction of the platform. These resources are sometimes divided into technical and social boundary resources. For further information, see *e.g.* Gawer (2009); Yoo *et al.* (2010); Ghazawneh (2012); Ghazawneh & Henfridsson (2013).

16 From a more technical point of view, smart contracts are autonomous programs situated in a certain address in the blockchain, which can be rerun infinitely and can also be programmed to contain a wide array of business model logics. Once the events specified in the contract take place and the transaction containing data arrives to the address of the smart contract, the distributed virtual machine of the blockchain executes the programming code of the smart contract in question. Ethereum is one example of this type of a blockchain platform with an integrated virtual machine layer which allows programs to be run in a fully decentralized fashion, and thus can facilitate smart contracts. See eg: http://ethdocs.org/en/latest/introduction/what-is-ethereum.html (23 August 2016). (BBVA Research, 2015)

17 At the moment, the most prominent of such platforms for smart contracts is a blockchain known as Ethereum (see https://www.ethereum.org/). For additional information on blockchain technology in general, see *e.g.* Mattila, (2016)

18 For more information on the role of smart contracts in the evolution of digital contracts in general, see *e.g.* Werbach & Cornell (2017); and Kõlvart *et al.* (2016).

19 The irreversibility of some contracts may prove to be a problem in some situations. This issue will, however, not be discussed further in this text.

20 Koulu, 2016, p. 65: "[...] *the smart contract operates with a similar logic to 'traditional' contracts: the will of both parties to enter the agreement is needed in order for it to be valid*".

21 It must be noted, however, that the aforementioned course of events is only a presumption, and the smart contract can also remain at a stage where it functions purely as a re-router built to transfer data or, for instance, the contents of one crypto-wallet to another (Bourque & Fung Ling Tsui, 2014,

p. 10). The legal status of such smart contracts can indeed be questioned with good reason, at least from the perspective of contract law. Therefore, their interpretation would seem to require case-by-case evaluation.

22 Section 1(1) of the Finnish Contracts Act (228/1929): "*An offer to conclude a contract and the acceptance of such an offer shall bind the offeror and the acceptor as provided for below in this chapter*".

23 Doctrinal research, or legal dogmatics, attempts to study law as it currently stands (see Hirvonen, 2011, p. 21–26).

24 For example Mika Hemmo has used these two terms as synonyms (see Hemmo, 2003, p. 10–11; Hemmo 2006, p. 26).

25 In Finland, "legal acts" can be concluded by all natural persons (ie humans) and legal persons for whom requirements have been set in order to have legal capacity. Questions about legal entities may arise especially in relation to decentralised autonomous organisations, but also about the different interpretations relating to the nature of smart contracts. Some researchers have considered smart contracts as agents based on algorithmic contracts acting for and on behalf of their principal, or even independent legal entities (see *e.g.* Scholz, 2017; Bourque & Fung Ling Tsui, 2014, p. 18–19). Questions about legal entities have their own connection to smart contracts, but that will not be considered any further in this text.

26 This characteristic has at least been heavily emphasised (see Hemmo, 2006, p. 24).

27 See *e.g.* Hemmo (2003, p. 19–24). So-called social civil justice emphasises the mutual trust between the parties and the principle of equity of contracts. An unreasonable contract or individual term may, therefore, be amended by the court for reasons of equity. This feature of Finnish contract law will most likely be applied to smart contracts as well. Only time will tell, however, whether courts will have the competence to evaluate whether a smart contract written in computer code is equitable.

28 These kinds of contracts, which require acting upon (the interposition of something), are called real contracts, and in legal literature have been considered to have very little importance in Finland. "*Reaalisopimuksen sitovuuden edellytyksenä on sopimuksen kohteen luovuttaminen toisen hallintaan*" [For a real contract to be binding the subject matter of the contract must be handed over to the other party's possession] (see Hemmo, 2003, p. 100, 180–181).

29 Finnish Contracts Act (228/1929, as amended): http://www.finlex.fi/fi/laki/ajantasa/1929/19290228#L3 (23 August 2016). The Contracts Act includes more detailed provisions about responses given on time, power of attorney and invalidity of juristic acts.

30 Implied contract or tacit agreement.

31 KKO 2010:23: "*Esimerkkeinä sopimuksista, joiden syntymisen edellytysten tarkasteluun oikeustoimilain periaatteet tuntuvat riittämättömiltä, on usein mainittu muun muassa erilaisia teknisiä välineitä, kuten automaatteja hyväksi käyttäen tehdyt sopimukset sekä sellaiset sopimukset, joita tehdään päivittäin ja toistuvasti suuria määriä ja jotka keskeiseltä sisällöltään ovat aina samanlaisia* [...]". [As examples of contracts the conclusion of which the principles of the Contracts Act seem insufficient to explain, two similar contract types can be mentioned: contracts concluded using various technical devices, such as automats, and contracts concluded again and again in large quantities which are essentially always the same by content.]

32 This may also be interesting in order to evaluate the effects on third parties, *i.e. ultra partes.* Even though the matter will not be discussed further in this text, it contains very important follow-up questions outside of contract law, *e.g.* in relation to tort liability, consumer protection, jurisdiction, conflicts of laws as well as dispute resolution.

33 This manner of concluding a contract includes some similarities to the aforementioned real contracts. While real contracts often require the subject matter of the contract to be lodged in the cus-

tody of the other party, it would have to be separately evaluated to what extent the transferred sum controlled by a smart contract could constitute such a subject matter.

34 Koulu, 2016, p. 65: "*The declaration of intent is not separate from the formation of the contract or from the execution of it*".

35 It is a question of its own whether this type of offer and its acceptance are precise enough to meet the requirements of the offer–acceptance mechanism. When an announcement alone that a party is willing to conclude contracts does not necessarily constitute an offer (but rather an invitation to make one), the smart contract in the blockchain might not be such a specific offer either (see *e.g.* Saarnilehto, 2009, p. 42–43).

36 What may become interesting is the type of situation in which a complex smart contract has a wide range of unspecified creators, where it may be impossible to identify the offering party. A compelling question here is for instance how a group like this can validly act as an offeror. This theme will not, however, be discussed any more widely in this article.

37 A different interpretation could be formed in a situation where it would be possible to commit to a smart contract by mistake or without understanding its true code-form content. These types of situations may be possible as the use of smart contracts becomes more popular, and it will be important to observe these situations in the future.

38 Despite previous evaluations, a smart contract is not, for example, a mechanical automat containing beverages, but rather a program which performs a specified action based on its programmed execution logic. A nearly infinite amount of different kinds of smart contracts can be programmed, so it is quite probable that not all smart contracts can be seen to involve the type of (at least implied) declaration of intent that is required to conclude a legally relevant act.

39 In this chapter we have discussed smart contracts in accordance with the definitions described previously in this publication. In addition, it has been considered that a smart contract only has one creator and is joined by only one other party.

40 The true intelligence of smart contracts can be questioned, as they do not contain artificial intelligence in themselves, as has been stated previously in this publication. A smart contract should thus be perceived as an automated mechanism which performs its defined functions as certain preconditions are met. The established term "smart contracts" is thus somewhat deceiving.

41 Another perspective to the smart contract in this example is that of contractual penalties. It could be interpreted that the deposit required from the seller in order to enter the agreement constitutes a contractual penalty clause.

42 Regarding the example, declaration of intent may manifest in different ways within the scope of the applied conclusion mechanism, depending on which party is the creator of the smart contract and which party is the one reacting to the smart contract. If a party of the arrangement does not act as the creator of the smart contract or react to it by making a payment or digital signature, their declaration of intent may be very difficult to prove.

43 For further information on ICOs, see *e.g.* Conley (2017).

44 This type of a smart contract seems to include characteristics of a contract containing conditions precedent or subsequent. In so-called conditional sales it can be agreed that the sale is only concluded if a certain future event takes place. Conditions subsequent refer to uncertain events. In this case the condition subsequent would manifest as the cancellation of the sale (and the return of the deposit to Y) in case the ICO fails to attract sufficient amounts of funding. For more about the conditions of a contract, see *e.g.* Saarnilehto *et al.* (2012, p. 401–402). Conditions and conditional sales will not be further discussed in this publication.

45 For a similar interpretation from the Estonian perspective, see also Kõlvart *et al.* (2016, p. 145).

46 Conversely, however, it is worth noting that if a traditional contract were to be created in code, this would require the contract to be arranged and presented as a process depicting interdependency: "if X, then Y, otherwise Z" (Mattila, 2016, p. 15). Since the way in which traditional contracts are worded can often result in ambiguity, this new use of formulas can in at least some cases reduce the need for interpretation (Wright & De Filippi, 2015, p. 11, 24–25). This kind of development can at best lead to significant reductions in the costs caused by drafting contracts and overseeing their execution.

47 Such questions may regard for instance the existence of a contract or the verification of its content (code vs the parties' true intent) as well as possible unintended errors left in the code. For such errors related to the intent of the parties, it is likely that section 32(1) (concerning the so-called error in declaration) of the Finnish Contracts Act can be applied if there is a conflict between content and intent due to an error in the contract code (see *e.g.* Hemmo, 2003, p. 396).

48 Dual Integration: "*The idea of dual integration is to allow users to be able to have the certainty of having a real world contract which can be taken to a court and enforced using established dispute resolution processes in the jurisdiction(s) of the user(s) while also using a smart contract as the primary mechanism for administering the data-driven interaction which attends to the agreement between the parties*" (https://erisindustries.com/components/erislegal/ (23 August 2016).

49 Out of these openly developed solutions the perhaps most significant one is Common Accord: "[...] *an initiative to create global codes of legal transacting by codifying and automating legal documents, including contracts, permits, organizational documents, and consents. We anticipate that there will be codes for each jurisdiction, in each language. For international dealings and coordination, there will be at least one 'global' code*". Well-known lawyer and crypto-oriented legal researcher Primavera De Filippi is part of the Common Accord group. See: http://www.commonaccord.org/ (23 August 2016).

50 One way to solve possible issues is by aiming to create general conditions of contract such as INCOTERMS or Creative Commons for the use of smart contracts. One such example is the Simple Agreement for Future Tokens (SAFT) initiative which aims to design a legally sound framework for carrying out initial coin offerings in accordance with the U.S. legislation. See: https://saftproject.com/ (5.12.2017).

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Article 5

Skimping on Gas: Reducing Ethereum Transaction Costs in a Blockchain Electricity Market Application

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Original publication:

Hukkinen *et al.* (2019). Skimping on Gas: Reducing Ethereum Transaction Costs in a Blockchain Electricity Market Application. Proceedings of the 52nd Hawaii International Conference on System Sciences.

Abstract

In recent years, information systems have not been largely evaluated by their operating costs, but mainly by their strategic benefit and competitive advantage. As blockchain-based decentralized applications become more commonplace, representing a shift towards fully consumption-based distributed computing, a new mode of thinking is required of developers, with meticulous attention to computational resource efficiency.

This study improves on a blockchain application designed for conducting microtransactions of electricity in a nanogrid environment. By applying the design science research methodology, we improve the efficiency of the application's smart contract by 11 %, with further improvement opportunities identified. Despite the results, we find the efficiency remains inadequate for public Ethereum deployment.

From the optimization process, we extrapolate a set of general guidelines for optimizing the efficiency of Ethereum smart contracts in any application.

1 Introduction

Over the past decade, digital platforms have transformed the provision of applications in digital networks (Constantinides, Henfridsson, & Parker, 2018; Tiwana, 2014; Yoo, Henfridsson, & Lyytinen, 2010). Traditionally, these platforms have been built using centrally controlled system architecture (Baldwin & Woodard, 2009; Boudreau & Hagiu, 2008). Recently, however, it has become increasingly popular to provide applications via decentralized blockchain smart contracts, governed by algorithmic incentives (Buterin, 2013; Wood, 2013). As the computational resources of these blockchain networks are allocated and priced according to free market mechanics (Catalini & Gans, 2016; De Filippi & Loveluck, 2016; Kroll, Davey, & Felten, 2013; Mattila & Seppälä, 2018), resource-efficiency and cost-optimization are placed in the center of application development.

The efficiency of information systems and business computing applications has not received wide attention in research lately. Ever since the 1980s, IT systems have not been mainly evaluated by their operating costs, but rather by their enhanced market access, product differentiation, strategic benefit and competitive advantage (Ives & Learmonth, 1984). The systems have been largely perceived as investments with long-term effects and benefits (Weill, 1992), across their whole lifecycle (Woodward, 1997) and most often emphasizing infrastructures, human resources and IT-enabled intangibles (Bharadwaj, 2000).

The advent of grid and cloud computing has gradually changed this long-term investment-based view to a short-term utility-based one. This change has produced some novel theoretical models on prices, revenues, and resource utilization (Bhargava & Sundaresan, 2004; Misra & Mondal, 2011). Also, more general considerations on the new economic models of cloud computing (Buyya, Yeo, Venugopal, Broberg, & Brandic, 2009) and grid computing (Buyya, Abramson, & Venugopal, 2005) have been published.

As blockchain technology moves computing as utility even further, a new mode of thinking is required of software developers, with meticulous attention to computational efficiency. While some theoretical research has focused on embedded costs (Easley, O'Hara, & Basu, 2017) and institutional changes (Davidson, De Filippi, & Potts, 2016) of blockchain, so far there has been little in the way of formal research into the optimization of blockchain-based smart contracts.

In the absence of a centralized authority, blockchain networks can consume vast amounts of electricity to maintain consensus (Kroll *et al.*, 2013). The Ethereum smart contract platform, for example, has been estimated to consume more electricity than the country of Iceland, constituting approximately 1/1000th of the world's electricity consumption in total (Digiconomist, 2020). Advancing the understanding and developing best practices in the optimization of blockchain-based smart contracts is important to ensure that the maximum innovation output and utility is achieved in return for the vast energy consumption of such systems and their strain on the environment at large (Murugesan, 2008).

The objective of this paper is to improve and analyze the feasibility of an experimental distributed blockchain market application designed for conducting microtransactions of electricity in a nanogrid environment (Hukkinen, Mattila, Ilomäki, & Seppälä, 2017; Mattila *et al.*, 2016). The paper applies the design science research methodology by Peffers *et al.* (2008) to explore novel ways to improve the efficiency of the application's smart contract and to reduce its operating costs in the Ethereum network. During this process, we introduce a new set of general guidelines for optimizing the efficiency of Ethereum-based smart contracts.

By implementing two of the identified improvement opportunities, we benchmark the efficiency of the smart contract improved by 11%. While not adequate for economic feasibility on the public Ethereum blockchain, we establish that further improvements are likely to be possible with more radical reformations to the source code, redefined market mechanics, and the use of an alternative deployment environment. Overall, the study demonstrates that decentralized applications should implement their own functional layers on top of the smart contract, keeping the contract as simple and as low in resource consumption as possible.

This paper is structured as follows. Section 2 provides a background for the paper by explaining some of the core technological concepts. Section 3 describes the blockchain electricity market smart contract analyzed and improved in this paper. Section 4 documents the process of optimization conducted in this study, starting with the problem identification and ending with the evaluation of the outcome. Section 5 contains some discussion on the findings. Finally, Section 6 presents the conclusions.

2 Technological descriptions

2.1 Blockchain technology

Blockchain technology enables the creation of decentralized, distributed and replicated digital ledgers. The technology itself consists of components such as peer-to-peer networking, public-key cryptography, digital tokens, a decentralized consensus algorithm and a tamper-resistant chain of blocks used to store database modifications (Nakamoto, 2008; Tapscott & Tapscott, 2016). Originally, the term was used solely in reference to the cryptographically concatenated data structure employed by blockchain systems such as the Bitcoin cryptocurrency network. Later on, however, the term has taken the broader meaning of the technological composition behind such systems at large, in various configurations (Mattila, 2016).

While cumbersome and often more expensive to operate than centralized systems, blockchain networks can be useful due to their tamper-resistant and non-hierarchical quality. Built on public open-source protocols, they can also help foster the growth of digital ecosystems with a bottom-up approach different from conventional centralized platforms. For this reason, cryptocurrency is an essential component of any permissionless blockchain. It can be used to facilitate economic incentives for the pseudonymous participants in the network to collaborate with one another and to maintain the integrity of the shared blockchain database (Constantinides *et al.*, 2018; Kroll *et al.*, 2013; Mattila & Seppälä, 2018).

2.2 Smart contracts

Blockchain technology has enabled the creation of decentralized execution environments for smart contracts. In comparison to conventional digital contracts, blockchain-enabled smart contracts expand the digital contracting space by enabling tamper-proof storage and decentralized algorithmic execution (Cong, 2018). Moreover, diverging from contracts concluded in the form of action, speech or writing, a smart contract is characteristically a computer program built in code (Buterin, 2013).

The concept of a smart contract is best explained by an example. A vending machine takes coins and a push of a button as inputs and dispenses change and a product as outputs. The vending machine always acts deterministically according to the same set of instructions. Inserting coins into a machine is seen as a sign of agreement with the terms of the vending machine's embedded contract. The vending machine is able to autonomously manage the process of handling a customer's money and selling a product without an external adjudicator (Szabo, 1997). Much in the same way as vending machines, digital smart contracts can essentially be characterized as cryptographic "boxes" containing value that only unlocks upon the fulfilment of the preconditions determined in their design (Buterin, 2013). Thus, they are able to handle the fulfillment of the contractual clauses embedded in their software without human intervention. Furthermore, they are able to penalize breaches of contract and prevent any unauthorized changes to their code (Lauslahti, Mattila, Hukkinen, & Seppälä, 2018; Szabo, 1997).

For this paper, we define smart contracts as digital programs that: a) are written in computer code and formulated using programming languages, b) are collectively stored, executed and enforced by a distributed blockchain network, c) can receive, store, and transfer digital assets of value, and d) can execute with varying outcomes according to their specified internal logic (Lauslahti *et al.*, 2018).

2.3 Ethereum

In recent years, blockchain technology has helped in overcoming the obstacles smart contracts previously faced. One such milestone was the launching of the decentralized application platform Ethereum in 2015. It offers a Turing-complete programming language for writing smart contracts and allows the deployment of smart contracts into its blockchain (Buterin, 2013).

Ethereum smart contracts can serve as a back-end for decentralized applications. The benefits of using an Ethereum smart contract instead of a new blockchain include faster and easier development, bootstrapped security, and being able to communicate with other decentralized applications deployed in the Ethereum blockchain (Buterin, 2013).

Ethereum utilizes a transaction fee system to prevent denial-of-service attacks and to incentivize efficient smart contract deployment. A transaction fee—or gas consumption—is determined by the amount of computational work, network bandwidth and storage space the transaction consumes (Buterin, 2013). This type of a fee system, instead of a simpler model, such as the one in Bitcoin, is required due to the Turing-complete programming language in which Ethereum smart contracts are implemented. The fee system must be able to charge on a per computational step basis in order to avoid the execution of infinite loops with infinite resource expenditure.

The contracts' code is run on Ethereum Virtual Machine (EVM) to ensure that the execution environment is always identical and hardware-independent. Every operation executed in the EVM is executed on every full Ethereum node, as nodes must validate new blocks before appending the blockchain.

3 A blockchain-based electricity market application

This section describes the Ethereum smart contract of the blockchain electricity market application analyzed in Section 4. The application provides a decentralized marketplace where nanogrid participants can sell excess electricity to one another. Since the marketplace is implemented as an Ethereum smart contract, it has no need for a central authority that could censor offers, steal users' deposits, or do front-running. In addition to providing a platform for making contracts and trading electricity, the application also inherently facilitates payment processing, using Ethereum's native cryptocurrency, ether.

For a smart contract to be useful for energy trading, a system composing of the following components is required: 1) a smart contract facilitating the marketplace; 2) a small-scale electrical network for delivering electricity (*i.e.* a nanogrid); 3) smart meters serving as access points to the nanogrid; and 4) a reputation system for assessing the trustworthiness of smart meters. However, in this paper, we do not specify the non-software components or the reputation system involved.

3.1 Electricity markets today and in the future

Due to the non-storable nature of electricity, supply and consumption must be constantly balanced in electrical grids. With multiple producers and consumers interacting with the grid, determining the price for each instance where supply and demand meet is vital for grid balancing. In most developed markets, price formation occurs at power exchanges, such as Nord Pool, where a range of power delivery contracts are used to balance the supply and the demand (Weron, 2007).

In EU countries, the percentage-share of renewable energy in gross final energy consumption has risen from 9 percent to 16.7 percent in a ten-year time span between 2005 and 2015 (European Environment Agency, 2017). Solar photovoltaic generation and many other renewable systems allow distributed generation near the points of demand, reducing transmission losses (World Nuclear Association, 2018). Such localized power production could transform the current vertical, centralized energy system into a more horizontal and distributed one. Conventional power generation, such as coal-fired power plants, allow power output to be steered to better match electricity demand. Therefore, given the price inelasticity on the demand side, grid balancing has traditionally taken place at the supply side (Bye & Hansen, 2008). However, with the growing share of intermittent renewable energy sources, future energy systems may require demand-side flexibility. Real-time pricing has been shown to affect demand and can be used to reduce curtailment (Finn & Fitzpatrick, 2014).

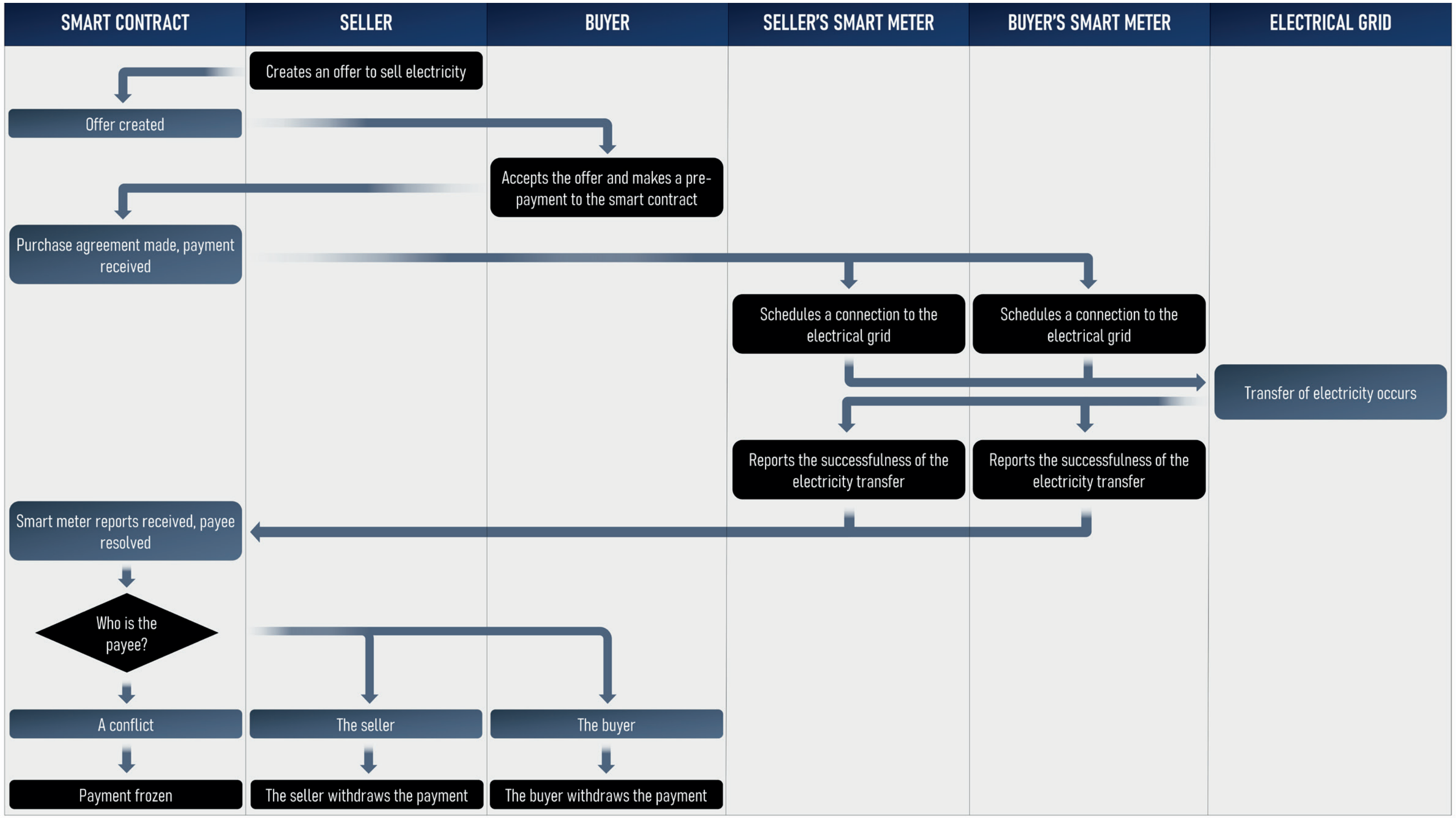
With photovoltaic systems and wind energy systems becoming accessible and affordable, energy generation may shift from large energy companies to smaller organizations or consumers themselves. This could spur the rise of small-scale electrical networks, microgrids and nanogrids, that can be isolated from the main grid thanks to local generation, consumption and control. In such circumstances, a distributed market mechanism would be beneficial for nanogrid balancing and enabling interconnectivity between separate nanogrids.

3.2 The process of transacting electricity

In the smart contract's logic, the process of an electricity transaction unfolds as follows (see Figure 1).

First, a user wishing to sell electricity makes a transaction into a smart contract situated in the blockchain, constituting a selling offer and specifying the terms of a proposed agreement. Any other user wishing to accept the offer and its terms may

Figure 1. A flowchart of the process of trading electricity in the marketplace facilitated by the smart contract. Each actor's actions are presented in a column of their own.



do so by submitting a prepayment for the purchase into the smart contract, thus expressing their intent to enter into a contract. The prepayment, at this stage, is not yet transmitted to the seller, but rather held by the smart contract facilitating the trade. This way, it would be unwise for the buyer to back out of the trade, already having irrevocably committed to making the payment. The seller, however, may fail to provide enough electricity, thus breaching the contract. Thus, a reputation system, that can penalize economically, is needed to prevent producers from doing so.

In the smart contract facilitating the transaction, two timestamps are specified: one for the starting time of the electricity transfer and one for the end of it. When the starting time occurs, the seller's and the buyer's smart meters allow the buyer and the seller to access the nanogrid and to transfer electricity. The smart meters act as gatekeepers for the nanogrid, preventing unauthorized electricity consumption or overload from occurring. The smart meters also record electric current and voltage during transmission, and using that data, they are able to tell whether the electricity transfer was successful.

After the time period allocated for electricity transfer is over, the two smart meters autonomously create blockchain transactions, reporting on the successfulness of the electricity transfer on their owner's side. Based on the reports, the smart contract decides who can withdraw the prepayment made earlier by the buyer. The desirable outcome is that both reports implicate a successful trade, and the seller may withdraw the payment.

Sellers can populate the electricity market smart contract with multiple offers and buyers can accept any offer that suits them best. All offers and agreements are processed fully transparently. As a result, a fair market price should be discoverable by the users.

3.3 Nanogrid characteristics

The electricity market smart contract has no notion of transmission costs or transfer losses in the electrical grid. Therefore, it is only suited for a compact nanogrid network where transmission costs of electricity are small enough to render them irrelevant when considering who to transact with. The electricity market application examined in this report assumes a fully interconnected nanogrid topology. In other words, each access point is directly reachable from every other point without having to proxy through another access point. The nanogrid needs to have a commonly agreed voltage and current type (alternating or direct current).

All participants of the nanogrid are connected to the nanogrid via a smart meter. Furthermore, although energy storing devices are not required from users, an ample use of batteries is expected locally behind the smart meters. To prevent outages in an interconnected nanogrid, each individual electricity transmission must happen exactly as planned. Throughout the timeframe specified in the smart contract, the seller is required to supply the network with the specified amount of power. In a parallel circuit, however, the lack of a consumption load on the buyer's side is non-critical.

3.4 Sale and purchase agreements

The contract includes the four specifiers necessary for any electricity transfer contract: delivery period (start and end time), recipient (seller's smart meter's Ethereum address), size of the transfer (amount of electricity), and price. An id field is also added, containing a 256-bit unique identifier for the contract. When a buyer accepts a seller's offer, the buyer's Ethereum address and their smart meter's Ethereum address are added into the contract. Finally, when the scheduled transmission of electricity is over, the seller's and the buyer's smart meters report whether in their view the transmission was successful or not.

3.5 Smart meters

Ethereum smart contracts only have access to data stored in the Ethereum blockchain. For this purpose, a smart meter is required for every user to act as an oracle (*i.e.* a trusted data feed into the blockchain) and to control the connection to the nanogrid. The smart meters either need to run their own Ethereum nodes or connect to an external trusted Ethereum node. For creating transactions, they must have their own Ethereum address and have access to their private key. The owners are expected to top up their smart meter's account with ether to maintain their ability to pay transaction fees.

Users of the electricity market application should not have full control of their smart meter, the software installed on it, or the private key of the smart meter's Ethereum address. Users should also not be able to bypass the smart meter and draw electricity directly from the nanogrid, as this would allow them to steal electricity and to manipulate results of the smart meter reports. Therefore, smart meters should be issued by a trusted party, presumably a company that manufactures or installs the smart meters.

3.6 Smart contract

The electricity market application involves two smart contracts written in the Solidity programming language. The `SmartMeters.sol` contract contains a mapping of smart meter addresses and their owners which the `ElectricityMarket.sol` contract is able to look up. In the `ElectricityMarket.sol` contract, there are five public, state changing functions: 1) `makeOffer`, used to signal the willingness to sell electricity; 2) `acceptOffer`, used to accept standing offers; 3) `buyerReport` and 4) `sellerReport`, used by the smart meters to report the successfulness of a transaction into the blockchain; and 5) `withdraw`, used to withdraw the deposit of a specified offer.

3.7 Scalability

A successful trade in the electricity market smart contract requires five Ethereum transactions, consuming a total of over 400 000 gas. According to the website etherscan.io, on the 12th of June 2018, the average gas limit per block in the public Ethereum chain was 7 996 828 and the average block time was 14.68 seconds. As a point of comparison, on the 13th of October 2017, the gas limit was 6 712 392 and the block time 31 seconds.

Were the public Ethereum chain to exclusively process transactions that call functions of the electricity market smart contract, the blockchain would be able to handle roughly one trade per second. A throughput like this is easily enough for a single community's nanogrid. However, it is not enough for widespread adoption of the application, processing trades of multiple nanogrids along with the transactions of all the other smart contracts on the public Ethereum chain.

Some method of increasing the scalability of the system is clearly needed. Either the application needs a significant reduction in gas consumption, or it needs to be executed in an environment other than the public Ethereum blockchain.

4 Applying the design science research methodology

In this section, design science research methodology by Peffers *et al.* (2008) is applied to the electricity market smart contract. Design science is a suitable research approach when an innovative, purposeful artifact is created and evaluated for a special problem domain (Hevner, March, Park, & Ram, 2004). In our study, we built an artifact and evaluated it to ensure its utility for the problem. By using the design, we demonstrate why the general blockchain solution must be improved in this particular problem domain. We selected design science as our methodology because it offers a rigorous method for designing, building and evaluating the artifact.

The methodology consists of a process model involving six activities: 1) problem identification and motivation, 2) defining the objectives for a solution, 3) design and development, 4) demonstration, 5) evaluation, and 6) communication. Since com-

Table 1. The cost of completing a trade in the electricity market at various points in time.

	GAS PRICE (GWEI)	ETHER PRICE (USD)	TOTAL COST (USD)
13TH OCTOBER 2017	26.49	$302.89	$3.21
14TH JANUARY 2018	58.39	$1385.02	$32.35
15TH FEBRUARY 2018	21.57	$920.11	$7.94
12TH JUNE 2018	14.04	$531.15	$2.98
28TH AUGUST 2018	12.80	$288.02	$1.48

munication, as described by Peffers *et al.* (2008), encompasses the entire research article, we will address activities 1–5 in this section.

4.1 Problem identification and motivation

In any public blockchain, a system of transaction fees is needed to arrange transaction priority, to prevent denial-of-service attacks, and to create an incentive for running the network and maintaining its consensus.

To complete a successful trade in the electricity market, the seller needs to spend roughly 290 000 gas on three transactions (calling the functions `makeOffer`, `sellerReport` and `withdraw`) and the buyer roughly 110 000 gas (calling the functions `acceptOffer` and `buyerReport`). From 13th of October 2017 to 28th of August 2018, according to etherscan.io, the transaction cost of a trade to the seller varied between $1.07 and $23.45 (USD), and to the buyer between $0.41 and $8.90, depending on the fluctuations of the gas price and the ether price during the observed time interval (see Table 1).

The cost of performing a trade sets a lower bound for the amounts of electricity that can be transmitted and thereby limits the possible uses of the application. For instance, it can never be profitable to sell electricity for one dollar, if the seller needs to pay two dollars in transaction fees.

Implementing an electricity market as a blockchain application has several advantages compared to a centralized service but these advantages can be thwarted by high operating costs. The problem identified in the electricity market smart contract is that, at the estimated cost level, the public Ethereum blockchain would not be a viable deployment environment for the electricity market application.

4.2 The objectives for a solution

In Ethereum, transaction cost is simply gas price multiplied by the amount of gas consumed by the transaction (Wood, 2013). To reduce transaction costs, at least one of these two values should be lowered. Gas price should generally not be controlled by Ethereum smart contracts, but instead selected by the user at the time of creating a transaction. This allows users to maintain the ability to choose between cheap transactions and getting their transaction included in the blockchain quickly. The amount of gas consumed, on the other hand, is a variable that can and should be optimized by smart contract developers. Ethereum's transaction fee system is built with the idea, that any use of computational, bandwidth or storage resources costs gas. Thus, making the contract less resource-intensive in any of these aspects will also reduce its gas consumption, therefore marking our objective.

4.3 Design and development

Trying to find inefficiencies in the smart contract's gas consumption, we approached each of the contract's five public functions individually. We first considered if there was a viable way of executing the function off-chain. If not, we examined if another method of improvement would be applicable. During this process, we identified and applied the following principles:

Avoid a design pattern where many new smart contracts need to be deployed, for instance, on a per-user basis. At a cost of 32 000 gas, contract creation is the most expensive EVM operation.

Keep the amount of transactions needed to interact with the smart contract low to diminish the impact of the transaction base fee of 21 000 gas. Design an interface with fewer functions that do more actions, rather than more functions that do fewer actions.

Optimize the smart contract's use of storage space. Whenever possible, use memory instead of persistent storage. Storing a word in persistent storage costs 20 000 gas, whereas storing a word in memory only costs 3 gas plus a memory expansion fee, whenever more memory is required. The memory expansion fee scales quadratically as more memory is needed, so memory should be used densely.

When the use of persistent storage is necessary, *consider if the stored data could be replaced with its cryptographic hash* on-chain, and the data itself could be stored off-chain.

Delete contracts and data stored in persistent storage that are not needed, in order to gain gas refunds.

Make use of off-chain transactions, using the blockchain only as an arbiter in case disputes happen.

During the analysis, it was identified that the `makeOffer` function can be removed from the smart contract entirely. Instead of announcing sales offers in the blockchain, offers can be cryptographically signed by their creator and sent to potential buyers in an off-chain communications channel, e.g. a peer-to-peer network. If a buyer later decides to accept the offer, the buyer must then include the sales offer along with the seller's digital signature as a parameter in their `acceptOffer` function call. This way, unaccepted offers do not needlessly bloat the blockchain yet a buyer can prove the authenticity of the offer by its digital signature.

The expected reduction in gas consumption from implementing off-chain offers is approximately 21 000 gas per a successful trade. This is due to not having to execute the `makeOffer` function anymore, and not needing to pay its transaction base fee. In addition to this saving, off-chain offers have the effect that offers that are never accepted by a buyer also never create a blockchain transaction, rendering them entirely free. This can be expected to enhance the efficiency of the electricity market due to much more efficient price discovery and lower transaction costs.

The functions `acceptOffer`, `buyerReport` and `sellerReport` do not seem as straightforward to execute off-chain. An on-chain `acceptOffer` call is necessary to make sure that only one buyer can accept a given offer and to prove that the offer was accepted before its expiration. The smart meter report functions have a strict deadline before which they must be submitted. An on-chain function call is a simple way to prove that this deadline has been met.

The `withdraw` function needs to be executed on-chain in order for the funds to be transferred on-chain. It was identified, however, that the current design where a separate call needs to be made for each transfer of electricity is not optimal. If users were allowed to withdraw funds from multiple electricity transfer contracts using a single `withdraw` call, fewer transactions would be required and less gas would be spent on transaction base fees. With this modification, we estimate the saving per electricity transaction to be 21 000−(21 000/n) gas, where 21 000 is the Ethereum base transaction cost, and n is the number of trades from which a user can withdraw funds using a single `withdraw` call.

4.4 Demonstration

During the design and implementation work, three artifacts were produced. Each artifact is a variant of the electricity market smart contract with some attempted improvements implemented. Artifact 1 implemented off-chain offers, as discussed earlier in Section 4.3. In Artifact 2, the `withdraw` function was modified so that it takes an array of trade IDs as argument and attempts to withdraw funds from all of the listed trades. Artifact 3 combines the changes implemented in Artifacts 1 and 2, with both off-chain offers and an improved `withdraw` function implemented.

A benchmark use case was executed on the artifacts, measuring the respective gas consumptions (see Table 2). The same benchmark use case was also executed on the original electricity market smart contract, to be used as a reference. The benchmark use case was crafted so that it represents typical use of the smart contract where a number of trades are completed successfully: 1) as a seller, create *n* number of offers; 2) as a buyer, accept all created offers; 3) as the seller's smart meter, report all trades to have been successful; 4) as the buyer's smart meter, report all trades to have been successful; and 5) withdraw all deposits to the seller's address.

The variable *n* in step one translates to the number of electricity trades completed in the use case. The test case was executed with different values of *n* to see how different implementations perform when varying amounts of transactions are created.

We measured the combined gas consumption of all the transactions created in the execution of the use case. The gas consumption of the transactions was inquired from the TestRPC instance using the `eth_estimateGas` function of the Ethereum JSON RPC API before the sending of each transaction. This function makes a transaction and returns its gas consumption but does not add the transaction to the blockchain. In a TestRPC configuration like the one used, the `eth_estimateGas` call is made to a blockchain of exactly the same state as its corresponding actual transaction, so the returned gas consumption estimate is equal to the true consumption.

The measurements were run on an Ubuntu 16.04.3 LTS machine. The Solidity smart contracts were compiled using the Solidity compiler solc version 0.4.18. A local instance of TestRPC version 6.0.1 was used to simulate an Ethereum blockchain. TestRPC was configured to create a separate new block for each transaction. A block gas limit of 90 000 000 was configured.

4.5 Evaluation

The results collected from the first artifact show that the implementation of off-chain offers did reduce gas consumption of the smart contract in the selected use case. In measurements where a few trades were made, roughly a 5 percent decrease in gas consumption was achieved. When more trades were made, this percentage gradually decreased. That is, however, due to the smart contract becoming more populated with data and certain phases in its execution having to spend gas on iterating that data. The absolute gas consumption savings achieved from off-chain offers do not seem to be reliant on the number of trades made, ranging narrowly from 20 784 to 20 816 gas per trade. This roughly equals to the base transaction fee of 21 000 gas, which was the expected saving from not having to call the `makeOffer` function

Implementing the ability to withdraw funds from multiple trades using a single transaction also led to savings in gas consumption, at best by over 6 percent. Surprisingly, with all *n* values other than 1, Artifact 2 created larger savings than the initially estimated 21 000−(21 000/*n*) gas per electricity transaction. With *n* values great-

Table 2. Gas consumption in artifacts 1–3 and the reference benchmark

NUMBER OF TRADES	REFERENCE NO IMPLEMENTATIONS	ARTIFACT 1 OFF-CHAIN OFFERS IMPLEMENTED			ARTIFACT 2 RENEWED WITHDRAW FUNCTION IMPLEMENTED			ARTIFACT 3 BOTH IMPROVEMENTS IMPLEMENTED		
	Gas consumed	Gas consumed	Difference (%)	Difference (gas)	Gas consumed	Difference (%)	Difference (gas)	Gas consumed	Difference (%)	Difference (gas)
1	400 318	379 534	-5.19	-20784	402 564	+0.56	2246	381 780	-4.63	-18538
2	787 210	745 578	-5.29	-20816	762 007	-3.20	-12602	720 397	-8.49	-33407
3	1 175 676	1 113 260	-5.31	-20805	1 123 024	-4.48	-17551	1 060 652	-9.78	-38341
4	1 565 716	1 482 516	-5.31	-20800	1 485 615	-5.12	-20025	1 402 481	-10.43	-40809
5	1 957 330	1 853 346	-5.31	-20797	1 849 780	-5.49	-21510	1 745 884	-10.80	-42289
6	2 350 518	2 225 750	-5.31	-20795	2 215 519	-5.74	-22500	2 090 861	-11.05	-43276
7	2 745 280	2 599 728	-5.30	-20793	2 582 832	-5.92	-23207	2 437 412	-11.21	-43981
8	3 141 616	2 975 280	-5.29	-20792	2 951 719	-6.04	-23737	2 785 537	-11.33	-44510
16	6 368 968	6 036 168	-5.23	-20800	5 959 480	-6.43	-25593	5 627 010	-11.65	-46372
32	13 125 496	12 459 832	-5.07	-20802	12 276 826	-6.47	-26521	11 611 844	-11.53	-47302
64	27 848 152	26 517 208	-4.78	-20796	26 121 121	-6.20	-26985	24 791 563	-10.98	-47759
128	62 128 792	59 466 520	-4.29	-20799	58 645 051	-5.61	-27217	55 985 573	-9.89	-47994

er than 4, the savings of the artifact exceeded the base transaction fee of 21 000 gas, which was anticipated to be the maximum gas saving opportunity for the artifact. We hypothesize that the extra savings at least partly originate from Artifact 2 only calling the Solidity send function once, while the reference implementation calls it *n* times. As a result, slightly less EVM code needs to be executed.

Artifact 3 was a combination of the changes in Artifacts 1 and 2: off-chain offers and the improved `withdraw` function. It is noteworthy that the gas consumption savings in Artifact 3 were almost exactly equal to the sum of savings gained in Artifacts 1 and 2. In other words, there was virtually no overlap in combining the two improvements.

While we were able to reduce the gas consumption of the electricity market smart contract in this study, the reduction was a little over ten percent at best. Assuming that the market participants are using batteries to ensure their capability to make successful trades, a typical trade in the electricity market could be estimated to be in the same order of magnitude as the capacity of a large car battery. A 12-volt 100 Ah battery could theoretically output 1.2 kWh of electricity. Assuming a price of $0.1/kWh, the electricity transferred in a typical trade would be worth $0.12. In section 4.1, we showed that at the market prices over the past year or so, the total transaction cost of a trade in the original smart contract, deployed in the public Ethereum blockchain, would have varied between $1.48 and $32.35. Even with the gas savings achieved, the transaction costs remain disproportionate, and in fact orders of magnitude too high compared to the value of a typical use of the application. This would suggest that the implemented optimizations are not adequate to make the application economically feasible on the public Ethereum chain, at least for transactions as small as suggested and at the examined price levels.

5 Discussion

While we were not able to improve the efficiency of the electricity market smart contract to the point of economic feasibility, this study demonstrates how blockchain-based smart contracts require a new kind of utility-centric focus on resource management in software development. Any Ethereum smart contract in any application should always seek to perform the absolute minimum set of tasks required from it. Whenever possible, decentralized applications should implement their own functional layers on top of the smart contract to keep the smart contract as simple and as low in resource consumption as possible.

The guidelines we produced for optimizing gas consumption of Ethereum smart contracts were successfully applied to pinpoint and fix inefficiencies in the electricity market smart contract. We estimate that the drafted guidelines are perfectly applicable for similar optimization tasks of any other Ethereum smart contract as well.

Although we used price ranges based on the price variation over the past year or so to estimate economic feasibility, it should be acknowledged that due to the chaotic nature of the system, future gas price dynamics are difficult to predict. While deemed unlikely, any radical drops in the real price of gas would require the feasibility findings of this study to be re-evaluated.

While having little impact on gas consumption in the benchmark use case, it was recognized that implementing off-chain offers could enable new types of price discovery mechanisms, potentially useful in other contexts. In a use case involving heavy use of selling offers that are never accepted, off-chain offers alone could reduce gas consumption significantly more than the 11% measured.

It is also quite possible that other improvable inefficiencies exist in the smart contract which were simply not identified or pursued in this paper. For example, a large share of the application's gas consumption is due to the use of persistent storage. We anticipate that significant gas savings could be achieved by only storing the hash of a sales and purchase agreement instead of its full details in the blockchain. The actual data could be hosted elsewhere, *e.g.* the Interplanetary File System (IPFS).

As an alternative to deployment in the public Ethereum blockchain, the Plasma child blockchains proposed by Poon and Buterin (Poon & Buterin, 2017), for example, may provide a viable platform for deployment in the future. A Plasma child chain could provide a similar execution environment connected to the Ethereum main chain, but with a lower demand for transactions, implying lower transaction costs. Another option would be to create a separate Ethereum blockchain instance entirely. While this would enable transactions at a mere fraction of the cost of the canonical Ethereum chain—or even completely free of transaction fees altogether—the lack of support for the ether cryptocurrency and for the security of the canonical chain could turn out to be problematic.

6 Conclusions

In this study, we explored ways to analyze and improve the feasibility of an experimental distributed blockchain market application designed for conducting microtransactions of electricity in a nanogrid environment (Hukkinen *et al.*, 2017; Mattila *et al.*, 2016). By applying the design science research methodology by Peffers *et al.* (2008), we managed to pinpoint inefficiencies in the design of the smart contract and to reduce its gas consumption by 11%. From this process, we formulated a set of general guidelines suitable for optimizing the efficiency of any Ethereum-based smart contract.

While the improvement achieved in efficiency was not adequate for economic feasibility on the public Ethereum blockchain, we established that further improvements are likely to be possible with more radical reformations to the source code, redefined market mechanics, and the use of an alternative deployment environment.

Further research is encouraged on the recognized improvement opportunities where additional efficiency gains could be achieved. We also invite the exploration of other new ways to improve the efficiency of Ethereum-based smart contracts. Furthermore, the price dynamics of gas and ether, and their effects on application feasibility, would benefit from a more structured delineation.

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Aalto University | DOCTORAL DISSERTATIONS 122/2021
ETLA Economic Research | Series A, No 51

ISBN 978-952-64-0503-2 (printed)
ISBN 978-952-64-0504-9 (pdf)
ISSN 1799-4934 (printed)
ISSN 1799-4942 (pdf)

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ISBN 978-951-628-711-2 (printed)
ISBN 978-951-628-712-9 (pdf)
ISSN-L 0356-7435
ISSN 0356-7435 (printed)

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