Participatory Multi-Criteria Decision-Making for Common Goods

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M.Sc. Sven-Erik Willrich

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Referent: Prof. Dr. Christof Weinhardt
Korreferent: Prof. i. R. Dr. Rudi Studer

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List of Abbreviations

AE	Allocation Efficiency
AHP	Analytic Hierarchy Process
APA	American Psychological Association
BFI	Big Five-Inventory
BMC	Business Model Canvas
BPMN	Business Process Model and Notation
CA	Conjoint Analysis
CBCA	Choice-Based Conjoint Analysis
CE	Choice Experiment
CI	Consistency Index
CPR	Common-Pool Resource
CR	Consistency Ratio
CSR	Corporate Social Responsibility
DAO	Decentralized Autonomous Organization
DLT	Distributed Ledger Technology
DM	Decision Maker
DoE	Design of Experiment
DSR	Design Science Research
DSS	Decision Support System
FCHR	First Choice Hit Rate
FI	Forest Invariant
FSDB	Forest State Database
HCI	Human–computer interaction
ICO	Initial Coin Offering
IS	Information System
IT	Information Technology
MCDA	Multi-Criteria Decision Analysis
MD	Mechanism Design

OR Operations Research
PC Pairwise Comparison
PCS Preference for Consistency Scale
PDMS Participatory Decision-Making System
PGT Public Good Theory
pMCDA Participatory Multi-Criteria Decision Analysis
SCF Social Choice Function
SDG Sustainable Development Goal
SW Social Welfare
TLX NASA TASK LOAD INDEX
TTP Trusted-Third Party
VCG Vickrey-Clarke-Groves

List of Symbols

$\mathbb{R}$	Set of all real numbers
$\mathbb{R}_+$	Set of all non-negative real numbers
$\mathbb{N}$	Set of all non-negative integers
$\emptyset$	Empty set
$\|A\|$	Cardinality of set A

Notations for Multi-Criteria Decision Analysis (MCDA)

o	Number of given criteria (or variables, attributes) in a decision problem
C_k	A set of manifestations of criterion k
C	A set of all criteria manifestation sets $C_1 \times \cdots \times C_o$
m	Number of given alternatives in a decision problem
A_j	A set of manifestations of criteria of alternative j
A	A set of all alternatives $A_1 \times \cdots \times A_m$
$\beta_{j,k}$	The part-worth utility of criterion $C_k \in C$ of alternative $A_j \in A$
y_j	The (overall) utility of alternative $A_j \in A$
X	A alternatives matrix $(x_{j,k})_{m \times o}$
p_k	The normalized (preference) weight of criterion C_k to a specific problem statement
p_k^i	The normalized (preference) weight of criterion k of agent i
p	The preference vector with normalized criteria weights $(p_1, \ldots, p_o)$
p^i	The preference vector with normalized criteria weights $(p_1^i, \ldots, p_o^i)$ of agent i

Notations for Pairwise Comparison (PC)

I	A set of items to be compared $I = (I_1, \ldots, I_f)$
w_a	The weight of item $I_a \in I$ (usually according the Saaty's scale of Table 3.1)
$\overline{w}_a$	The normalized weight of item $I_a \in I$
$\overline{w}$	The normalized priority vector $\overline{w} = (\overline{w}_1, \ldots, \overline{w}_f)$ of items $I = (I_1, \ldots, I_f)$
$m_{a,b}$	The importance ratio of item I_a to item I_b
M	A pairwise comparison matrix $(m_{a,b})_{f \times of}$ for $a, b = 1, \ldots, f$

Notations for Game Theory

n	Number of given agents
N	A set of given agents, i.e $N = 1, \ldots, n$
θ_i	A preference of type of agent i
$\widehat{\theta}_i$	Type announced by agent i
Θ_i	Set of all types of agent i
Θ	$\Theta_1 \times \cdots \times \Theta_n$, the set of all type profiles

Part I

Introduction

Chapter 1

Introduction

> There is no reason to believe that bureaucrats and politicians, no matter how well meaning, are better at solving problems than the people on the spot, who have the strongest incentive to get the solution right.
>
> Elinor Claire "Lin" Ostrom

1.1 Motivation

Common goods are omnipresent in our daily life. They reach from a parking area to natural fish stocks, over forests to – in a broader sense – digital goods like the internet. They share commonalities with infrastructure-related goods and have strong relations to public services being in general interests. Because its offerings are accessible by (like the right to the entrance in German forests) and have utility for (e.g. biodiversity or carbon storage) everyone, they are typically in everyone's – the so-called public – interest. The world's public and common goods offer natural resources, which provide social, ecological, and economic value for everyone, while the preferences over these offerings diverge. The thesis at hand illustrates these interest-driven preferences by the forest – being representative for a common good (Ostrom, 2008; Meurs, 2007).

Forests are a unique ecosystem covering almost four billion hectares, or 30 % of the earth's surface (Bundesministerium für Ernährung und Landwirtschaft (BMEL), 2008). They offer a variety of functions for humans and nature, for example as a vital source of raw materials or for climate and species protection. By now, it has not been possible to stop their progressive destruction and degradation. Natural forests are being destroyed on a large scale, especially in the tropics. The problems of poverty, unsustainable land use, or weak government structures are too great. One main driver for these problems is the economic attractiveness of other forms of land use, which often lead to large-scale conversion of natural forests, due to the global demand for soya, palm oil, and other agricultural products. At the same time, forests offers renewable resources, conserves biodiversity, acts as a carbon sink, and provides recreational functions in a simultaneous manner – to just mention some. While these goals are conflicting, solving these conflicts remains an inevitable task.

Our Common Future is a report that was released in 1987 by the Word Commission on Environment and Development (WCED). It starts a serious debate about how sustainable development of the world's future is possible (Ostrom, 2008). The debate is about the question on how to manage global resource systems, or common goods. In line with this, the United Nations General Assembly has set a collection of 17 global goals, the "Sustainable Development Goals" designed to be a "blueprint to achieve a better and more sustainable future for all" in 2015 – accompanied by the intention to achieve these goals by the year 2030 (Griggs et al., 2013). Furthermore, the Federal Ministry of Education and Research of Germany has declared the discipline bioeconomy (biobased economy) as the topic for the year 2020. Bioeconomy should contribute to sustainable development and green growth. It describes a transformation to create products and processes within an economy in a more sustainable way. In the political debate, the development of bioeconomy is closely related by societal goals. Bioeconomy can be understood as to integrate social, ecological, and economical goals and it can be applied to the forestry. However, since these goals – to some extent – are in conflict among themselves, they cannot all be reached simultaneously. For example, once the ecological goals are fully achieved, the economic goals can not be equally fully achieved. Or to be more specific: When everyone would stop to intervene in forests, wood could not be deforested in order to sell it. To moderate between these goals and to increase the acceptance for decisions in forestry, participation is a proven measure in forestry (Buchy and Hoverman, 2000), which leads also to an increased satisfaction among stakeholders (Teder and Kaimre, 2018), and was further successfully applied in combination with Multi-Criteria Decision Analysis (MCDA) (Ananda, 2007) to tradeoff between these goals. Although these endeavours are appreciated, challenges remain – such as general open access for people interested in participation and incentives to participate. Further, selfish people who behave strategically in a participatory decision-making situation, or a larger number of criteria to describe decision-making outcomes more precisely. The work at hand tackles these challenges by engineering a Participatory Decision-Making System (PDMS).

Challenges on Participatory Decision-Making for Common Goods

When it comes to participatory decision-making to solve these goals, satisfying each participant's preferences completely is not possible by nature. For example, it is common sense that increasing both the utilization and the protection function of a forest in an arbitrary way is not possible and there exists a threshold at which a further increase will result in an inevitable decrease in another function. Compromises can then be used to tradeoff between parties and can help to fit everyone's interest at best. However, when multiple agents are involved to decide over a common good, and they are assumed to be rational and interested in maximizing their individual utility, this easily could lead to a situation known as the *collective action problem* or *free-rider problem* (Baumol, 2004). Such decision problems are shaped by individuals who might under- or overestimate preferences to manipulate the outcome – additionally supported by the fact that, by definition, nobody can be excluded from consuming the common good. Once preferences are coupled with mandatory contributions in a monetary unit (e.g. the willingness to pay), incentives are given to behave strategically. This is the case when individual rationality does not result in group rationality (Olson, 2009). Instead of cooperation, which might yield a better outcome for all (i.e. a pareto-efficient outcome), competition leads the individuals to behave selfish while maximizing their own utility (for more details, see Chapter II). Since peoples' dominant strategies are to maximize their own utilities (in theory), as long as no cooperation have been decided, the performance of common goods or of forests is below its potential. Though a pareto-efficient outcome would desirable for everyone – due to the absence of cooperation and missing incentive alignment –, these outcome can not be supposed to happen among rational decision-makers.

With the above explanations given, forest management might be more aligned towards the productive function instead of recreational or protection functions. Recreational or protection functions are not worth realizing due to their non-monetarization – hence, economical goals are pursued by, as observed globally (Ostrom, 2008), exploitation of the productive function. Due to the non-monetarization of these ecosystem services, economical-driven owners have less incentives to align forest management along everyone's interests, such that bio diversity services, infrastructure in the forest, climate resistance of some tree species versus preserving local tree species versus tree species with short rotation period – in Germany, approximately half of the forest is owned by private forest owners (UNIQUE forestry and land use GmbH, 2018).

The work *The Tragedy of the Commons* (Hardin, 1968) describes this situation along the usage of common goods. According to that theory, individual users of a common good act selfish and therefore contrary to the common good. In this model, the collective action of all results in an overuse of the common good. In last decades, humans have failed to prevent common goods from further overuse, e.g., by overfishing the oceans, excessive dumping of carbon dioxide in the atmosphere – or global major deforestation. Put it more technically, similar to the *collective action problem* described above, the users of the common good finally fail to reach a pareto-efficient outcome because they pursue strategies that maximize their individual utility.

1.2 Research Outline

This thesis discusses participation in the field of common goods to co-decide management alternatives, here illustrated by the forest. It understands the forest management problem in a multi-criteria sense and assumes to have self-interested people with diverging interests over these criteria. They act – in a game-theoretical sense – strategically to reach their goals, i.e., acting according to those strategies promising highest (expected) utility for themselves. Each person is interested in enforcing its interests best possible.

At this stage, Information Technology (IT) has brought out powerful tools that might help to tackle some of the above-mentioned challenges. An individual (or a group of individuals) assumed to be given, an Information System (IS) can respond to the information demand of that individual (or the group of individuals). With the right incentive structure in mind, individuals share private information and reduce information asymmetry among themselves. The more information are made public, the better an IS can then satisfy information demand. A Decision Support Systems (DSS) is an IS supporting decision makers while making such decisions (Bonczek, Holsapple, and Whinston, 2014) – even in groups (Ricci, Rokach, and Shapira, 2015). It can receive (or derive from historical data) preferences from users and recommend (optimal) decisions. Since forest management decision problems usually consist of multiple criteria due to its complexity, Multi-Criteria Decision Analysis (MCDA) approaches are established in this field. MCDA itself is a powerful methodology to incorporate diverging preferences, to solve multi-objective problems and has therefore been proven to be a valuable methodology in the forestry (Kangas and Kangas, 2005) over the last three decades (Ananda and Herath, 2009). Many MCDA approaches were combined with group decision-making (Matsatsinis and Samaras, 2001), which have also been applied in public participation for the forestry (Kangas, 1994) and are used within DSS (Adomavicius, Manouselis, and Kwon, 2011). In this context, DSS are also able to tackle MCDA and participation to support compromises (Wibowo and Deng, 2013). Once a problem statement consists of multiple criteria, multi-objective optimization approaches can be used to provide pareto-efficient solutions.

Participatory decision-making can be further addressed by mechanism design (and public good theory), a sub discipline of game theory. At this, mechanisms are used to incentivize the achievement of a predefined goal. Therefore, mechanism design means to define rules and incentive structures in such a way to reach a desired outcome. When it comes to participatory decision-making for common goods and the *collective action problem*, mechanism design can help out to tackle the afore-mentioned challenges. Parkes and Ungar (2001) distinguished four different sources of complexity across two layers when designing mechanisms: (1) the agent layer refers to the complexity agents are faced with while declaring their own type (1.1), i.e., which outcome they prefer and to what extent they have weights and preferences over possibly multiple outcomes. (1.2) refers to the complexity agents are faced with while determining the own strategy in a multi-agent setting, i.e., how to behave to increase the own utility. The second layer (2) is about the infrastructure, where the complexity to determine the result for everyone (2.1) and the complexity to communicate between agents to determine the result belong to (2.2).

Following this, this research puts special focus on 1.1, where MCDA is used to help the agents determine the best outcome, and on 1.2 to establish incentives, to make it individually rational with a dominant strategy to report truthfully – which is necessary to ensure the allocation to be efficient at the end. The complexities 2.1 and 2.2 are infrastructure-related and are affected by a powerful technology called Distributed Ledger Technologies (DLTs) (also known as Blockchain).

DLT is an emerging technology whose potentials are not completely known so far. DLTs, in short (for broader explanations, see chapter II), are databases that are characterized by storing its data like a chain in a decentralized way. These data are usually stored in blocks that are concatenated to a chain by "reverse-linking", i.e, each block stores a hash of and links to its predecessor. DLT has most probably reached its broad attention by its original invention by Nakamoto (2008) aiming at revolutionizing payment transactions without intermediaries like banks with Bitcoin. With the emergence of smart contracts (Ethereum Foundation, 2017), DLT is far more than just a distributed ledger storing states in a block-wise manner. Although DLT was initially discussed with cryptocurrencies, nowadays applications reach from voting systems (Osgood, 2016) to digital organizations (Jentzsch, 2016a) – partly positioned in the field of cryptoeconomics. DLT-based governance is gaining popularity (Beck et al., 2016; Böhme et al., 2015). DLT is able to connect people together with a reduced degree of trust (Hawlitschek, Notheisen, and Teubner, 2018). These people are then usually working together for a shared goal (money transactions (Nakamoto, 2008) or voting (Yavuz et al., 2018)). As mentioned, forest management is ideally aligned to the public interests. While doing so, DLT themselves shares some commonalities with common goods – a public DLT is open by design, therefore nobody is excludable which makes it similar to a common good. Since decentralized approaches make central manipulations and corruptions (in forestry (Irland, 2008)) impossible, and people need to interact and to coordinate themselves while decision-making, DLT might be a promising candidate here.

Given this development, the first research question starts with a structured literature review to review the state-of-the-art of DLT usages in the fields of bioeconomy and especially the forestry. Therefore, the research starts with:

> **Research Question 1:** *How is the Distributed Ledger Technology (DLT) used in the field of bioeconomy?*

With these findings in mind, challenges towards the management of bioeconomy, and especially the forestry, but also – in more general – the commons are identified. By taking past and contemporary usages of DLT into consideration, DLT seems to be a promising candidate to help organize and conduct group decision-making – in particular if selfish people pursuing own interests are given and no Trusted-Third Party (TTP) can be chosen to organize the necessary coordination for group decision-making centrally. This leads to a qualitative research where an IS is sketched in a conceptual way that fulfills group decision-making with respect to common goods, illustrated by the forest. The research objective is, by a requirement-driven approach, to design a DLT-based system, i.e., a – in this work named – Participatory Decision-Making System (PDMS) where participation and DLT-based governance are brought together. This research is driven by the question:

> **Research Question 2:** *How needs a DLT-based Participatory Decision-Making System (PDMS) be conceptualized to fulfil participation requirements?*

Until then, the research does not consider different DLTs and it has not yet been examined which DLT might be suitable for the given use case of PDMS. Therefore, the next research gap is filled by a quantitative and literature-driven research in order to apply a systematic decision analysis on different DLT alternatives that were examined against the background of thoroughly elaborated decision criteria. In particular, the decision analysis followed the framework of the Analytic Hierarchy Process (AHP), a special methodology within the field of Multi-Criteria Decision Analysis (MCDA). This systematic analysis approach took a set of DLT alternatives and a set of DLT decision criteria into account and derived a recommendation for that DLT alternative that give highest utility with respect to a PDMS as described by research question 1. This leads to:

> **Research Question 3:** *Which Distributed Ledger Technology (DLT) has the highest utility for that use case for a Participatory Decision-Making System (PDMS)?*

Participation and decision-making can be closely related to each other. In the work at hand, participation is mainly driven by the idea of involving participants into the decision-making process, with special regard to the DLT's adding-value features described by Sultan, Ruhi, and Lakhani (2018a), i.e., transparency of data (or information), immutability of data (or information), the distribution of data (or information), and the way consensus is achieved about the data (or information). This is why the research questions before ask for the design, the acceptance and expected utility, and which DLT to use for such a system (the PDMS). Group decision-making might change the decisions individual decision makers make, because they are not alone in the decision-making situation. They make expectations about the preferences of others or even know the preferences of others, resulting in decision adjustments on the level of individuals (rational decision makers assumed). It might therefore affect the way the individual decision makers are in exchange among themselves. A DLT enables decision makers to be in exchange without need for trust to intermediaries. That way, group decision-making by IT for a common good, such as a forest, is possible even when no Trusted-Third Party (TTP) can be used (see research question 2 for arguments explaining the justification of a DLT).

Further research focuses more on the decision-making itself. The involved people (or 'agents' in a game-theoretical sense) should decide / vote in a honest and precise way. Especially, they might decide / vote in a strategical manner (in a game-theoretical sense). Further, it is assumed that these agents are selfish and self-interested over the outcomes. There are many feasible solutions to a forest management problem, but only some (a subset) satisfy the Allocation Efficiency (AE) condition. AE is satisfied once all agents' preferences are inserted in a trustful manner (incentivized by incentive-compatibility) and such a solution is determined by which Social Welfare (SW) is maximized. At this point, there is no solution given that can make someone better without making someone else worse – a situation called to be Pareto efficient. To put it differently, that forest management alternative with highest agents' utilities in sum maximizes SW and is hence to be selected. The research objective is therefore to design a mechanism for decision situations with multiple alternatives and criteria, that incentivizes participating agents not to behave strategically. When all individuals signal (see Narahari, 2013, on page 210) their preferences honestly (i.e. do not behave strategically), all pertinent information for an optimal outcome computation are available. This is the basis for the determination of an alternative that maximizes SW. Once the agents have incentives to deviate from honest signaling, because it is the promising way (a dominant strategy) to maximize their individual utilities, they reveal misleading information. In the following, the outcome can not be computed in a Pareto efficient way, since the received individual information are wrong. Therefore, the research focuses on the question:

> **Research Question 4:** *How to incentivize truth-telling in participatory multiple-criteria decision-making over management alternatives of a common good?*

This research includes Public Good Theory (PGT) (referring common goods), Mechanism Design (MD) (a subdiscipline in game theory), and MCDA and is conducted in a analytical way and by means of a agent-based simulation. The research consists of a problem formulation for a common good, an analytical argumentation, and results of the agent-based simulation where the agents' strategy room is completely enumerated to show that strategy-proofness (a strong degree of the above-mentioned incentive compatibility) (see Narahari, 2013, on page 238) is given.

After engineering a PDMS by DLT, next research is driven by acceptance and utility questions. By means of a mixed approach of Multi-Criteria Decision Analysis

(MCDA) combined with (part-worth) utility theory of Conjoint Analysis (CA), it has been analysed in which target group and to which extent a PDMS (as described by research question 1), which is based on DLT and applied to the forestry sector, give utility. The self-made questionnaire is designed in such a way that the DLT-features adding value in terms of participation are described, to which the respondents are asked for judgments. For that reason, respondents were partly asked by a guided personal interview and partly by an online study. This self-made questionnaire was pre-evaluated by five students. This interview-based and quantitative research give first insights and is driven by the research question:

> **Research Question 5:** *To what extent of utility does a Participatory Decision-Making System (PDMS) give to whom and does the Distributed Ledger Technology (DLT) add value in participation?*

Besides the question on how to achieve truth-telling in a multi-criteria decision situation in terms of participation, another focus lies on the question on how to support the precision of judging preferences. Someone might cause deviations between the given preference and the true preference for some reason, i.e., it could be of strategic advantage to misreport preferences, which might be a simple misrepresentation of true preferences. This situation might be caused by a complicated methodology to quantify preferences (e.g. at the Analytic Hierarchy Process (AHP), see Kwiesielewicz and Van Uden, 2004) in order to insert these into a system for further decision-making purposes. People are sometimes facing uncertainties and might only be able to express preferences in a fuzzy way, which also causes problems in group decision-making and – of course – in reaching SW. Because the decision-making here is based on MCDA and many MCDA methods are existing, the AHP approach is considered, since the AHP is one of the best known, and its popularity is quite high (see Velasquez and Hester, 2013b; Saaty and Vargas, 2012). As a rule, the AHP undertakes judgments by means of Pairwise Comparison (PC) (Saaty, 2002) to elicit relative importances between criteria. However, among decision makers, PC is not well-liked (Zardari et al., 2015b). This might be caused by the fact that the full design of PC has some disadvantages, e.g., (1) inconsistencies between PC judgments, (2) the fast-growing number of comparisons, and (3), hence, the time-consuming judgment effort for decision makers, which results in a PC cognitively challenge. PC has further advantages over so-called absolute weighting methods, e.g. rating scale, likert scale, point allocation, since it uses relativeness among criteria as measurement. It can often be assumed that it is not known or at least uncertain to what extent a criterion is to be weighted absolutely. Then, a relative scale, operationalized by measuring a criteria always in relation to another, can be used. Instead of using a full design for PC, it might also be possible to use a reduced design of PC (in particular by taking the approach of Koczkodaj and Szybowski, 2015b, into consideration) with a strongly reduced number of comparisons required. Consequently, inconsistencies are not possible (by design) and the fast-growing number of comparisons is avoided. This leads to the research objective on how the reduced design performs in comparison to the (classic) full design method. Furthermore, because PC results in many pairs to be judged, a visualization could help to keep an overview and to give an orientation. Both research questions combined lead to the following research question:

> **Research Question 6:** *A reduced design of Pairwise Comparison (PC) integrated in the Analytic Hierarchy Process (AHP): Is it better or equal to the full design?*

> **Research Question 7:** *Does a bar diagram affect the performance when displaying the relative importances of the criteria during the Pairwise Comparison (PC) phase?*

These research questions were answered by an online-experiment conducted with 100 respondents for each of the four treatments (reduced design versus full design and with bar diagram versus without bar diagram). The reduced design of PC by Koczkodaj and Szybowski (2015b) is benchmarked against the full design of PC and a classic CA. To compare the performance, the respondents were finally asked to put preferences in a simulated choice situation based on a Choice Experiment (CE).

1.3 Structure of the Thesis

The work at hand is structured in five parts as shown in Figure 1.1. The first Part I introduces the topic, gives a motivation, describes and derives the research questions. The next Part II describes the key concepts and foundations this work is based on.

The Parts III and IV consist of the key contributions of this thesis. Part III consists of a literature review given in Chapter 5 with a broad overview about today's DLT usages and Chapter III with a conceptualization of a DLT-based approach for sketching a Participatory Decision-Making System (PDMS). In Chapter 7, a best suited DLT to the previously proposed PDMS is determined. Part III concludes with a game-theoretical analysis of participatory decision-making in a multi-criteria setting in Chapter 8. Part IV consists of a study, which examines the utility of DLT in combination with participatory decision-making in forestry in Chapter 9 and concludes with the planning, the execution, and the results of an online-experiment in Chapter 10. Exactly this structure is shown in Figure 1.1 where the research questions introduced in Section 1.2 are positioned next to the chapters where they are answered. This thesis concludes with Part V where the results are summarized, a critical review to the overall work is provided, and an outlook including further directions are presented.

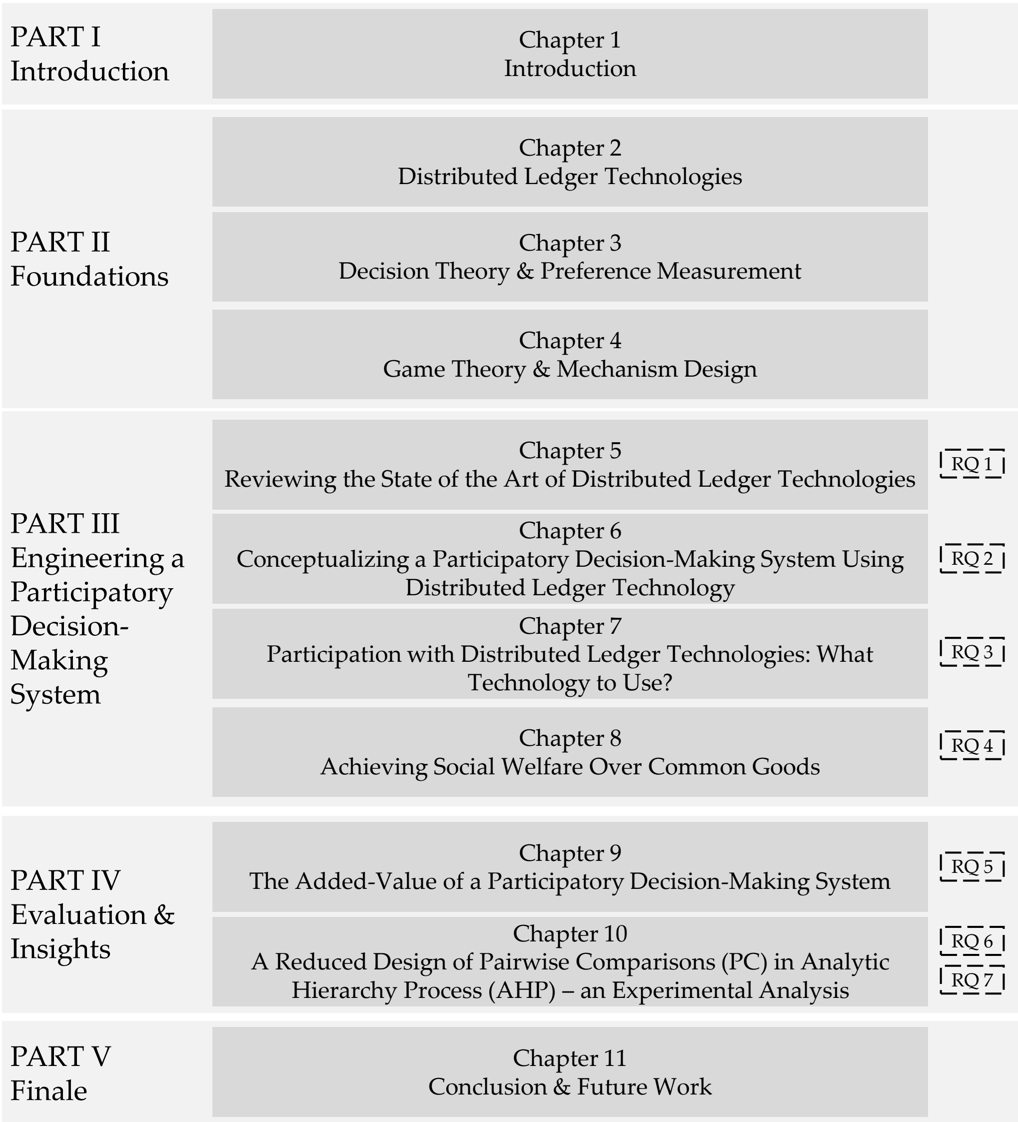

FIGURE 1.1: Structure of thesis

Part II

Foundations

Chapter 2

Distributed Ledger Technology and Governance

> All one needs to do is read - books, magazines, research the Internet - and pay attention to the influencers in their lives to discover the myriad people of strong moral character who have and still are making positive, meaningful contributions and differences in our world.
>
> Zig Ziglar

With the publication of the white paper "A Peer-to-Peer Electronic Cash System" by Nakamoto (2008) and the resulting Bitcoin as initiator and pioneer of blockchain Technology. Thus, the emergence of Distributed Ledger Technology (DLT) has highly likely begun with the understanding of blockchain by Satoshi Nakamoto who is referred to as a person or a group of people (Nakamoto, 2008). After rapid increases in the rate of Bitcoin in 2013 and 2016 (the Bitcoin price closed in 2013 at around 5400 % of the price at the beginning of the year), the Bitcoin and thus blockchain received immense media attention (Berentsen, 2017). The dependencies between media attention and Bitcoin prices are investigated by Philippas et al. (2019). The financial world experiences an unprecedented run-up to crypto currencies which are developed as so-called "AltCoins" as a result of the whole topic. Cryptocurrencies are the original and most obvious form of blockchain applications (Garriga, Arias, and De Renzis, 2018; Swan, 2015a).

Many established companies such as IBM, UBS, and Nasdaq launched their own research projects on blockchain. The projects are primarily concerned with low-cost and fast settlement in securities trading, self-executing contracts, as well as possible applications for networking devices via the Internet of Things (Berentsen, 2017). The development of these new types of systems, loosely built on the original Bitcoin blockchain concept, result in the emergence of a new, more generic term Distributed Ledger Technology (DLT) (Hileman and Rauchs, 2017). Hileman and Rauchs (2017) show a significant change from the use of blockchain towards DLT as an umbrella term for "all these new systems that are built on the premise of enabling a shared database between parties seeking to reduce the need for trust or depending on an intermediary". In practice, it can be observed that both terms, that is blockchain and DLT, are sometimes used interchangeably, which leads to a mistakenly use. Furthermore, Hileman and Rauchs (2017) introduce a simple framework to distinguish between traditional distributed databases, distributed ledgers, and blockchains. Distributed ledgers can be referred to as a subset of distributed databases, as well as blockchains are one level underneath of distributed ledgers.

Until now, there has been invented and established a lot of different DLT (among all DLT, the blockchain technology is actually one of many others). A DLT can be understand as one potential implementation of DLT (Cachin, 2016). In general, the invention of blockchain was mainly driven by the endeavor to revolutionize the way transactions (of, for instance, money) are done. Their hope was to reduce the necessity of intermediaries such as banks - with the overall goal to establish and use a medium where trust into such central institutions is no longer a prerequisite for exchanging values or information (Hawlitschek, Notheisen, and Teubner, 2018). As conceptualized, the DLT potentials come from its distributed structure – resulting in the possibility to avoid intermediaries. Where trust in platforms can become a problem, DLT provides an alternative. Hence, intermediaries, such as lawyers, brokers, or bankers, cease to be a vital or indispensable part of transactions. Through its shared ledger and its consensus mechanisms, transactions are persistent in a transparent, immutable, and traceable way (Nakamoto, 2008) and, consequently, protected from deletion, tampering, and revision (Iansiti and Lakhani, 2017).

Today, DLT integrates several fields and combines software engineering, distributive computing, cryptographic science, and economic game theory (Sultan, Ruhi, and Lakhani, 2018a). That way, DLT is no longer just a cryptocurrency. Today, it is applicable to so much more use cases, e.g. governance is gaining more and more attention in the Information Systems (IS) literature (Beck et al., 2016; Böhme et al., 2015). Furthermore, a DLT may offer the ability to trigger transactions automatically. This automation is possible by smart contracts. With this feature at hand, a DLT is empowered to execute Turing complete programs that are able to react when certain conditions are met (based on the implemented contract logic) and then to trigger events (Buterin and Others, 2014). With those smart contracts, it is possible to write a so-called Decentralized Autonomous Organization (DAO) as a digital and decentralized autonomous company (Swan, 2015c).

2.1 Further Generations of Distributed Ledger Technology

With the Ethereum infrastructure in 2015 ("A Next Generation Smart Contract & Decentralized Application Platform (2013) Whitepaper") and its own currency Ether, a further development of the previously known blockchain technology was introduced to the market. It is often referred to as blockchain 2.0 (Swan, 2015b) or the *second generation of DLT* applications (Garriga, Arias, and De Renzis, 2018), which took off after 2014 (Swan, 2015b). The difference is the provision of a general platform on which so-called smart contracts can be traded and executed, which are created and managed using the Ether currency. Thus, the use of Ethereum exceeds the pure use as currency and has further functions such as virtual shares or membership certificates through the smart contracts ("A Next Generation Smart Contract & Decentralized Application Platform (2013) Whitepaper"). This is handled via so-called Decentralized Apps (DApps) as applications on the Ethereum platform ("A Next Generation Smart Contract & Decentralized Application Platform (2013) Whitepaper"). According to Swan (2015b), additional second generation DLT projects are Ripple (see ripple.com), Counterparty (counterparty.co), Ethereum (ethereum.org), Mastercoin (mastercoin.org), NXT (nxtcommunity.org), Open Transactions (opentransaction.org), Open Assets (github.com/OpenAssets), Colored Coins (coloredcoins.org), and Bit Shares (bitshares.org).

When reaching the third generation of DLT, one comes across different definitions and scopes of the term blockchain. Yang et al. (2018) separate between smart contracts and decentralized apps (and define the difference between blockchain 2.0 and blockchain 3.0. As smart contracts and decentralized apps are inherently connected, the definition contributed by Yang et al. (2018) for blockchain 3.0 is not formally verifiable in terms of coinciding with other classifications. As DLT are currently widely-spread researched, the third generation cannot be precisely delineated.

DLT are currently being further developed with different scopes. On the one hand, the development of non-blockchain blockchains Hays (2018) can be recorded. On the other hand, the further development to DLT, which in their application focuses on extensions in the areas of social interaction and needs as well as general human life such as government, health, science, literacy, culture, and art. Governance plays an important role here (Swan, 2015b).

2.2 Governance by Distributed Ledger Technology

This section deals with another field of research, which is also extensively researched at the moment. The research field can be summarized with Governance by Blockchain or Blockchain government. The usage of the term DLT instead of blockchain widens the horizon of possible future applications, which is why this script uses the term DLT government or Governance by DLT for that topic.

The basis of the research in governmental environments is the call for more decentralization, flexibility, and adaptability of administration and control systems in organizations of all kinds (communities, enterprises, small groups and others). Decentralization in governance can improve the efficiency and responsiveness of the public sector by bringing decision making closer to citizens (Dillinger and Fay, 1999). By defining such governance by means of a distributed system, decentralized administration, and a democratic consensus mechanism are intended to create transparent governance with all participation through decentralization. The idea is to use DLT to provide services that are "traditionally provided by nation-states, in a decentralized, cheaper, more efficient, personalized matter" (Swan, 2015b). A major implication of DLT governance is the fact that governmental actions and services could be implemented more individually/ tailor-made instead of continuing the mass market-oriented (on community level) provision of public goods. A personalization of public services for a public repository or record, which is a fitting use case for DLT and can be solved by the benefits that DLT brings with itself (Swan, 2015b). A vision of the research in DLT governance is a profoundly more representative democracy. Involving fewer people in the governance apparatus could potentially mean a smaller, cheaper government, less partisanship and less government driven by special interest lobbyists. Because DLT makes financial systems more efficient and reduces marginal costs to zero, DLT could also redesign governance and public administration tasks. Cost savings could then be shifted directly to basic income support initiatives to promote equality and political participation in society and facilitate the transition to an automated economy (Swan, 2015b). Swan (2015b) illustrates these visions by providing various scenarios for this purpose: "An example of personalized governance services might be that one resident pays for a higher-tier waste removal service that includes composting, whereas a neighbor pays for a better school package. [...] One example of more granular services could be a situation in which smart cities issue Roadcoin to compensate passing-by drivers'. Prisco (2014) illustrates his Governance by DLT visions as the entire world being represented in a DAO. The discussion here already goes from off-chain solutions, where the governance structure is not stored and distributed on the actual blockchain, to on-chain governance solutions that have the advantage that decentralization is fully and significantly more secure than with off-chain implementation (Xu et al., 2017). When using on-chain governance, "rules for instituting changes are encoded into the blockchain protocol. Developers propose changes through code updates and each node votes on whether to accept or reject the proposed change." (Ethereum Foundation, 2017). The criterion of decentralization in terms of governance, for example, is much better in DLT and Ether than in traditional governance models, but still to an unsatisfactory degree because large shares of power lie with the developers or miners and mainstream users are excluded.

2.3 Decentralized Autonomous Organization

As mentioned above, the concept of DAO raises popularity as it was added by the Ethereum Foundation to their public DLT protocol (Jentzsch, 2016a). It is strongly aligned to DLT-driven governance that is decentralized and trust-less. To setup a decentralized governance on a DLT, there might be rules that describe how the organization handles different situations when certain conditions are met. Beside the technical specifications of decentralized governance, there are also social-economic impacts on how organizations are steered and managed. Because there is no central authority on top of the organization, it is possible to create a distributed, self-organized, and non-hierarchical social structure (Reijers, O'Brolcháin, and Haynes, 2016). The main purpose of a DAO is the decentralized governance of "computerized rules and contracts" (Chohan, 2017a) in a transparent manner. Furthermore, it is common sense that today's organizations are usually coordinated and controlled in a centralized way – in this case, a classical top-down flow is applied. In contrast, a DAO follows a bottom-up approach. In the start-up phase of a DAO, an initial coin offering (ICO) takes place. That way, tokens (used synonymously to coins) are offered and can be bought by shareholders who then participate in a group / co-decision decision process where different voting systems can be used (Pilkington, 2016).

The exact legal status of the organizational-type of a DLT is yet undetermined. DLT are still considered inexpressible or at the very least extremly hard to describe. For this reason, researchers and experts have so far had difficulty in agreeing on a concrete definition (Jentzsch, 2016b; Chohan, 2017b). Chohan (2017b) attempts to find a suitable definition. Following this, a DLT can be referred to as an organization that functions by rules that are encoded via computer programs, so called smart contracts. An import role plays the blockchain maintaining the DAO's financial transaction record and transcript and its governance. In effect, this immensely increases transparency and security. "The conceptual basis of a DLT has been typologized by an underlying ability of blockchain technology to provide a secure digital ledger that tracks financial interactions across the internet, bolstered against forgery by a method known as trusted time stamping and by dissemination of a distributed database" (Chohan, 2017b). The term DLT has first come to appearance in the early years of Ethereum applications when the basic extensions of the existing DLT were spread by the application possibilities by means of smart contracts. Ethereum founder Buterin ("A Next Generation Smart Contract & Decentralized Application Platform (2013) Whitepaper") refers to DLT as "long-term smart contracts that contain the assets and encode the bylaws of an entire organization.".

Chapter 3

Decision Theory & Preference Measurement

> All one needs to do is read - books, magazines, research the Internet - and pay attention to the influencers in their lives to discover the myriad people of strong moral character who have and still are making positive, meaningful contributions and differences in our world.
>
> Zig Ziglar

Multi-Criteria Decision Analysis (MCDA) is a branch of operations research and deals with structuring and solving of problems (Zhou and Ang, 2008). Within the MCDA, it can be distinguished between multi-objective decision making (MODM) and multi-attribute decision making (MADM). While MODM deals with a continual solution space and side conditions to constrain the solution space, MADM deals with a discrete solution space, i.e., the number of solutions is limited and denoted as alternatives (Zimmermann and Gutsche, 1991). The MCDA (more specifically MODM) can be divided in five steps, which are processed in sequential order (with the possibility to repeat steps). After the problem is identified (1), (2) the problem is structured, consisting of selecting the alternatives and determining the goal to be achieved. Afterwards, (3) the decision model is created, i.e., the set of criteria that best quantify the preselected alternatives is derived, and subjective judgements are applied between the criteria. In these two last mentioned steps, the selection of criteria and alternatives must be conducted in a methodically clean way, i.e., these tasks are characterized by a very thoroughly procedure and thus usually consume a major part of the overall time. In the next step (4), the model itself is reviewed and sensitivity analysis is processed to increase the certainty and acceptance of decisions (Geldermann and Lerche, 2014). In the last step (5), the decision making takes place.

3.1 The Analytic Hierarchy Process

The Analytic Hierarchy Process (AHP) is special implementation of a multitude of several methods in the discipline Multi-Criteria Decision Analysis (MCDA) and lies in the intersection of the fields decision analysis and hard operations research (Brunelli, 2014). The AHP was first introduced in 1970 by Saaty (1980) and Saaty (2002). The method is known as a well-established and widely accepted (Vaidya and Kumar, 2006a) method to elicit expert's preferences in a systematic way and is able to translate those into an understandable and traceable decision-making. The method is usually applied to a given problem statement (or use case) that is described by a set of decision criteria $C = (C_1, \ldots, C_o)$ and a set of alternatives $A = (A_1, \ldots, A_m)$. An alternative $A_j \in A$ has to be a technical feasible and, by decision makers, accepted solution to the problem statement given. The decision criteria might be structured as a hierarchy as described by Saaty (1980) (this is where the name is originating from). The method is divided into two basic judgement phases, i.e, (1) a judging phase among the decision criteria with respect to the problem statement and (2) a judging phase between the decision criteria and the alternatives. At both (1) and (2), the weighting method PC is used.

The first phase (1) results in a normalized priority vector $p = (p_1, \ldots, p_k, \ldots, p_o)$ where $p_k \in \mathbb{R}$ for each $k = 1, \ldots, o$, depicting the subjective weight of a criterion k with respect to the overall goal (the problem statement). For the priority vector p, the condition $\sum_{k=1,\ldots,o} p_k = 1$ holds. As described below and especially by Equation 3.9, the priority vector can be calculated by $p = PCV(C)$.

The second phase (2) results in a alternatives matrix $X = (x_{j,k})_{m \times o}$ describing the alternatives in a quantitative way with $k = 1, \ldots, o$ and $j = 1, \ldots, m$ as shown in Equation 3.1.

$$X = (x_{j,k})_{m \times o} = \begin{array}{c} \\ A_1 \\ \vdots \\ A_j \\ \vdots \\ A_m \end{array} \begin{array}{c} \begin{array}{ccccc} C_1 & \cdots & C_k & \cdots & C_o \end{array} \\ \begin{pmatrix} x_{1,1} & \cdots & x_{1,k} & \cdots & x_{1,o} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ x_{j,1} & \cdots & x_{j,k} & \cdots & x_{j,o} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ x_{m,1} & \cdots & x_{m,k} & \cdots & x_{m,o} \end{pmatrix} \end{array} \tag{3.1}$$

That way, the matrix in 3.1 contains the alternatives row-wise and the criteria column-wise. The values in the cells represent the manifestations of the corresponding criterion in the corresponding alternatives, that is $x_{j,k}$ represents the manifestation of criterion $k = 1, \ldots, o$ at alternative $j = 1, \ldots, m$. The matrix X is a complete quantitative description of the alternatives with respect to the given criteria. For the alternatives matrix X, the condition $\sum_{j=1,\ldots,o} x_{j,k} = 1$ for each $k = 1, \ldots, m$ holds.

Following the AHP, the matrix X is the result of many PC tasks. For each criterion $C_k \in C$, a PC matrix is calculated as described by Equation 3.4, resulting in o PC matrices (plus that one for the criteria themselves). That is, for each $C_k \in C$, a PC matrix is constructed $X_k = PCM(A)$ and a priority vector is derived $p_k = PCV(A)$ (note that the denotation p is reserved for the priority vector for the importance of decision criteria with respect to the problem statement while the denotation p_k is reserved for the priority vector to described the alternatives). In the equation

$$p_k = PCV(A) = (x_{j,1}, \dots, x_{j,k}, \dots, x_{j,o})^T$$

the occurrence of the priority vector of alternative A_j is depicted, which is also contained by the Equation 3.1.

After the alternatives matrix X (see Equation 3.1) and the decision maker's priority vector $p = (p_1, \dots, p_k, \dots, p_o)$ are calculated, the synthesis phase aggregates both values to a part-worth utility $\beta_{j,k} = p_k * x_{j,k}$ and provides a y_j for the (total) utility of alternative j as shown in Equation 3.2.

$$y_j = \sum_{k=1,\dots,m} \beta_{j,k} \tag{3.2}$$

After that, the winner alternative is chosen by $\max_{j=1,\dots,m} y_j$, that is the alternative maximizing the utility.

3.1.1 Pairwise Comparison

In general, a Pairwise Comparison (PC) is an activity where two objects are compared among themselves. The respondent is asked whether the left or the right one is more important (if neither the left one nor the right one is more important, it is common to allow indifferent judgements).

Within AHP, the PC is used by the decision maker(s) to judge both the priority vector (1) $w = (w_1, \dots, w_k, \dots, w_o)$ and the values of the matrix X of Equation 3.1 (2). For comparisons, the PC by Saaty (2002) uses the established and well-accepted Saaty's scale of importances shown in Table 3.1. By means of this scale, each comparison is made by the decision maker following the question whether left (or the right) one is equal, more, or less important to the right (or the left) one.

This section describes the general creation procedure for a square and reciprocal PC matrix $M = (m_{a,b})_{f \times f}$ that is applicable both to (1) and (2) as described above and illustrated in Equation 3.4. For this purpose, let define items to be compared with $I = I_1, \dots, I_f$ and a and b indices referring to these items $I_a, I_b \in I$. Here, the indices a and b can be equal to the criteria denotations $a, b = 1, \dots, o$ or, for the alternatives, $a, b = 1, \dots, m$. Let further define $w = (w, \dots, w_f)$ for weights about

Intensity of Importance	Definition
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong importance
9	Extreme importance

TABLE 3.1: Saaty's importance scale (Saaty, 2002)

these items $I = (I_1, \ldots, I_f)$ where

$$w_a \in (\frac{1}{9}, \frac{1}{7}, \frac{1}{5}, \frac{1}{3}, 1, 3, 5, 7, 9)$$

usually based on the Saaty's scale shown in Table 3.1. For example, if item I_a is *Strong important* over I_b, then $w_a = 5$ and, due to reciprocity, $w_b = \frac{1}{5}$.

To reach a complete PC matrix, there are many sub-comparisons required. Equation 3.3 shows how many sub-comparisons are necessary to be able to build a complete PC matrix, when f different items are given.

$$\frac{(f-1) * f}{2} \tag{3.3}$$

In the resulting PC matrix, each entry is positive $m_{a,b} > 0$ and as outlined by Saaty (2002), each entry is assumed to approximate the ratio between the weight of two items being in comparison

$$m_{a,b} \approx \frac{w_a}{w_b} \; \forall \; a, b = 1, \ldots, f$$

and reciprocity is especially understood by $m_{a,b} = \frac{1}{m_{a,b}}$ (Mühlbacher, Axel, C. and Kaczynski, 2014). The diagonal values are subject to $a = b$ is $m_{a,b} = 1$ since equal items are equal important. With $m_{a,b}$, the degree of preference (or importance) of I_a to I_b is expressed.

$$M = (m_{a,b})_{f \times f} = \begin{matrix} & 1 & \cdots & b & \cdots & f \\ 1 & 1 & \cdots & m_{1,b} & \cdots & m_{1,f} \\ \vdots & \vdots & 1 & \vdots & \vdots & \vdots \\ a & m_{a,1} & \cdots & 1 & \cdots & m_{a,f} \\ \vdots & \vdots & \vdots & \vdots & 1 & \vdots \\ f & m_{f,1} & \cdots & m_{f,b} & \cdots & 1 \end{matrix} \tag{3.4}$$

3.1.2 The Priority Vector

On the basis of a PC matrix, the *priority vector* can be derived and is depicted as $\overline{w} = (\overline{w}_1, \dots, \overline{w}_f)^T$. Each element $\overline{w}_a \in \overline{w}$ is subject to $0 < \overline{w}_a < 1$ and sums up to 1

$$\sum_{a,\dots,f} \overline{w}_a = 1$$

expressing the normalized and relative importances among the items compared. The reach such a priority vector $\overline{w}$, several procedures are in discussion in literature (see Brunelli, 2014) and each method yields ratings for PC in terms of synthesizing. At this, of course, different methods lead different results. In this work, two well-established procedures are used and presented in the following, i.e., the *Eigenvector method* and the *Geometric mean method*.

According to Brunelli (2014), the most popular method to estimate a priority vector has been proposed by Saaty (2002) himself. Following Saaty (2002), the priority vector should be the principal eigenvector of M as shown in Equation 3.4. That way, to yield that priority vector, Equation 3.5 shows the equation system to be solved.

$$\begin{cases} Aw = \lambda_{max} w \\ w^T 1 = 1 \end{cases} \tag{3.5}$$

After solving the equation system of Equation 3.5, λ_{max} is the maximum eigenvalue of A and $1 = (1, \dots, 1)^T$.

Another way of computing the priority vector is the *geometric mean method* by Crawford (1987) that is more easily to compute and therefore also oftentimes applied by practitioners (and researchers as well) (Brunelli, 2014). According to this procedure, the geometric mean is created for each row and divided by the sum of these geometric means, as depicted in Equation 3.6.

$$\overline{w}_a = \frac{\left(\prod_{b=1}^{f} m_{a,b} \right)^{\frac{1}{n}}}{\sum_{c=1}^{f} \left(\prod_{b=1}^{f} m_{c,b} \right)^{\frac{1}{n}}} \tag{3.6}$$

3.1.3 Inconsistencies

Since the judgements by means of PC are done by decision makers, the judgments might prone to a certain degree of fuzziness and decision makers might be faced with a certain degree of uncertainty (particularly for the case of Analytic Hierarchy Process (AHP), see Kwiesielewicz and Van Uden, 2004). In this sense, a lot of scientific work (Saaty, 2002; Brunelli, 2014) was devoted to the question on how to deal with *inconsistencies* at the PC. Several indices and procedures have been elaborated to face these occurrences in order to (1) indicate a certain degree of inconsistency or (2) to optimize procedures best possible to avoid the occurrence of inconsistency by design. As summarized by Brunelli (2014), decision making underlies oftentimes the assumptions described by the sentence

> A *single* decision maker is *perfectly rational* and can *precisely* express his preferences on *all pairs* of *independent* alternatives and criteria using *positive real numbers*.

where the explicit assumptions are highlighted in italic. Further, it is supposed that a consistent PC matrix is given as long as the transitivity condition of Equation 3.7 holds for each $a, b, c = 1, \ldots, f$ in $m_{a,c} = m_{a,b}m_{b,c}$, for instance, if $m_{a,b} < m_{b,c}$ and $m_{b,c} < m_{c,d}$, then $m_{a,b} < m_{c,d}$ and vice versa for various preference relations (equal, greater, or lower than). Nevertheless, the occurrence of inconsistencies is is rather usual than seldom (Brunelli, 2014, page 28)).

$$m_{a,b}m_{b,c} = \frac{w_a}{w_b}\frac{w_b}{w_c} = \frac{w_a}{w_c} = m_{a,c} \tag{3.7}$$

The Consistency Index

One way to deal with inconsistencies is to compute a Consistency Index (CI) and a Consistency Ratio (CR) in order to show up the degree of (in)consistency or to ensure consistency. A complete PC matrix given, the maximum eigenvalue λ_{max} is equal to f if and only if the matrix is consistent. The value is greater than f otherwise. As described by Saaty (1977), the Consistency Index (CI) is calculated by

$$CI(M) = \frac{\lambda_{max} - f}{f - 1}$$

and normally a non-standardized measure because the results of $CI(M)$ differ between matrices of different sizes, i.e., a matrix with size f has another value if $f + 1$ at $CI(M)$. Several numerical studies shows that the expected value of $CI(M)$ by processing many randomized (and therefore inconsistent) matrices M grows with the size of the matrix f. This is why a Consistency Ratio (CR) was introduced as a rescaled version of CI. At this, the CR should be ≤ 0.1, otherwise the probability of having randomness given is greater than 10 %, which is usually a threshold and rejected in practice (Brunelli, 2014). For a given matrix M of order f, the CR

$$CR(M) = \frac{CI(M)}{RI_f}$$

is obtained by dividing the CI by a real number of a RI_f. The values of RI_f come from an estimation of the average CI obtained by a large set of randomly generated matrices of size f and are outlined by Table 3.2.

f	3	4	5	6	7	8	9	10
RI_f	0.5247	0.8816	1.1086	1.2479	1.3417	1.4057	1.4499	1.4854

TABLE 3.2: Values of RI_f (Alonso and Lamata, 2006)

Functional Wrappers of Pairwise Comparison

Since in different chapters are referred to the computation of a PC matrix, we use, for the sake of simplicity, the notation of Equation 3.8 to compute a PC matrix where PCM is a function that takes items $I = (I_1, \ldots, I_f)$ as input and gives back a PC matrix $M = (m_{a,b})_{f \times f}$.

$$PCM : I \rightarrow M \tag{3.8}$$

Because it is sometimes more necessary to have a priority vector given, the notation in Equation 3.9 depicts a function PCV where, items $I = (I_1, \ldots, I_f)$ are mapped to a priority vector representing the item's normalized importances.

$$PCV : I \rightarrow \overline{w} \tag{3.9}$$

3.2 Pairwise Comparison Simplified

Another approach to conduct Pairwise Comparison (PC) has been proposed by Koczkodaj and Szybowski (2015b). As argued by Koczkodaj and Szybowski (2015b), in many cases, an incomplete PC matrix is given and should be completed resulting in a consistent decision matrix as shown by Equation 3.7. For explanations, the same indices, notations, and functions are used as previously introduced.

The way a PC matrix is "simplified" is by completion. The completion mechanism described by Koczkodaj and Szybowski (2015b) does not further assume a PC matrix to be complete, especially there are not

$$\frac{(f-1) * f}{2}$$

sub-comparisons required as depicted in Equation 3.3 and takes the above introduced items $I = (I_1, \ldots, I_f)$ into account. Instead of, the approach get with just $f - 1$ comparisons along.

3.2.1 Preconditions

Before the algorithm can start to complete an incomplete PC matrix, there are some preconditions that must be satisfied. First, the pairs for the PC must be determined. In order to do this, the selection of pairs follows a systematic approach and must not be arbitrary, though they may be generated in a randomized way. As outlined by Koczkodaj and Szybowski (2015b), it is assumed that a matrix

$$P = ((a,b), m_{a,b})_{f-1}$$

is given with $f-1$ rows, which contains the pairs $(a,b) \in (a,b)^{(\frac{(f-1)*f}{2})}$ with $a, b = 1, \ldots, f$ to be judged (e.g. I_a in comparison to I_b) and the variables of the PC matrix

$$M = (m_{a,b})_{f \times f} = \begin{matrix} & \\ 1 \\ \vdots \\ a \\ \vdots \\ f \end{matrix} \begin{matrix} \begin{matrix} 1 & \cdots & b & \cdots & f \end{matrix} \\ \begin{pmatrix} 1 & \cdots & m_{1,b} & \cdots & m_{1,f} \\ \vdots & 1 & \vdots & \vdots & \vdots \\ m_{a,1} & \cdots & 1 & \cdots & m_{a,f} \\ \vdots & \vdots & \vdots & 1 & \vdots \\ m_{f,1} & \cdots & m_{f,b} & \cdots & 1 \end{pmatrix} \end{matrix}$$

with $m_{a,b}$ as already shown by Equation 3.4. At this, the indices a and b are two indices designating a pair (a,b) that is presented the decision maker for comparison. When generating matrix P, the following conditions must hold:

1. P must contain at least each element of I, i.e. $\exists!\, a \in (a,b) \in (a,b)^{(\frac{(f-1)*f}{2})}\, \forall\, a, b = 1, \ldots, f$
2. P must be exact of size $|P| = f - 1$
3. P is a tree, i.e. when the pairs are understood as edges and the indices (representing the items) as vertices (which can be checked using DFS (depth-first search) algorithm)
4. the elements of $a, b \in (a,b)$ are different and must be in order, i.e. $a < b\, \forall\, a, b = 1, \ldots, f$

3.2.2 Algorithm for Completion

With these preconditions in mind, the Algorithm 1 is parameterized by P, f, and an incomplete PC matrix m. To work with P, $P_{k,1}$ refers to the k'th pair (a,b) in P while $P_{k,2}$ refers to the variable $m_{a,b}$ of Equation 3.4.

$$\sum_{i=a \in P_{k,1}}^{b \in P_{k,2}-1} x_i = \log(P_{k,2}), \;\; \forall\; k = 1, \ldots, f-1 \tag{3.10}$$

Algorithm 1: Reconstruction of a Pairwise Comparison (PC) matrix

```
Data: m, P, f
for i ← 1 to f by 1 do
    m_{i,i} = 1
for i ← 1 to f − 1 by 1 do
    m_{i,i+1} = 10^{x_i} ;                              // see Equation 3.10
for i ← 1 to f − 1 by 1 do
    for l ← i + 2 to f by 1 do
        m_{i,l} = ∏_{j=i}^{l−1} m_{j,j+1} ;             // due to transitivity
for i ← 1 to f − 1 by 1 do
    for l ← i + 1 to f by 1 do
        m_{l,i} = 1 / m_{i,l} ;                         // due to reciprocity
```

The Algorithm 1 is exactly executed once. The executing starts with an incomplete PC matrix m and ends up with a completed version of it. During the phases sketched in the algorithm, the matrix is filled step-by-step. Given a pair (i, l), the algorithm starts with these values having no distance between themselves $l - i = 0$ and assign them a 1. Values having a distance of exactly $l - i = 1$ are assigned by means of the values of the linear equation system of Equation 3.10. The next step consists of using the transitivity condition to fill up all values having a distance of $l - i > 1$ and the last step consists of the completion by the reciprocity condition (the distance does not matter).

3.3 The Conjoint Analysis

The Conjoint Analysis (CA) was first mentioned in the work of Luce and Tukey (1964) and introduced as methodology for market research methodology by Green and Srinivasan (1978) in 1970s. In general, the CA is also known as "Conjoint Measurement" (Backhaus et al., 2016). In today's usage, the initial method is known as traditional and or classic CA or profile method. In 1980s and 1990s, further methods are adopted from here and Choice-Based Conjoint Analysis (CBCA) (Erhardt, 2009) and the adaptive CA (Louviere and Woodworth, 1983) were developed. Today, the CA is one of the most frequently used methods to elicit customer's preferences in a quantitative way.

The CA is used to quantify customer's preferences in order to gain information about customers. The goal of a CA is to quantify the utility (or importance, preference) of attributes or levels of attributes by judging stimuli. That way, stimuli might have a (overall) utility and level of attributes might have a part-worth utility (Steiner and Meißner, 2018a).

The procedure of the conduction of a CA (see Backhaus et al., 2016, on page 501) can be described by

1. Determining attributes and attributes levels of the stimuli being in question.
2. Survey design, i.e the way the preferences are elicited from the customers.
3. Judging of the stimuli (or attributes, once hybrid or more sophisticated approaches are used, e.g. the CBCA)
4. Estimation of (part-worth) utilities
5. Aggregation of the (part-worth) utilities

With respect to the first step, the attributes must be relevant for the preferences of customers, must be influenceable by the designer, they must be independent (by design), their levels must be realizable, their levels must be in a compensatory relation, and must not contain attributes or attribute levels that are exclusion criteria for someone (Weiber and Mühlhaus, 2009).

Backhaus et al. (2016) presented two questions for designing the survey. The first question is whether to use a profile or a two factor design while the other is more related to the question whether to use a reduced or full design for the stimuli. Since in this thesis, the first questions is not important (for more information, see Backhaus et al., 2016, on page 503), only the second one is presented. The number of stimuli is highly fast increasing. A survey design consisting of just three attributes and three attribute levels per attribute, the total number of resulting stimuli is $3^3 = 27$. The *full profile method* is used once the survey designer uses all possible combinations of the attribute levels while a *reduced profile method* tries to get along with a subset of it.

3.3.1 Survey Design

Especially, as far the designer of a survey (or experiment) is faced with critical resources such as respondents (humans), thoughts should be given on the way the data are elicited. Therefore, the survey design is one of the most important activities. Design of Experiment (DoE) is a term referring to the way the data are elicited. That way, the respondents' effort and cognitive load might be strongly lower as a result since the number of judgements might be reduced. At this, the objective of a *reduces profile design* is to find a subset of the overall combinations being contained by the *full profile design* that is best-suited to represent the full profile design. Instead of pulling a randomized sample of the profiles given in the full profile design, the designer usually uses a symmetric or asymmetric design. In the symmetric design, all levels of the attributes have the same size. Let $C = (C_1, \ldots, C_o)$ be a finite set of o attributes and $c \in C_k$ a level (oftentimes also referred to as manifestation) of attribute k. Then, a symmetric design has the same number of levels across all attributes, i.e. $|C_1| = ... = |C_o|$. A special design of a reduced profile design is the latin square with $|C_1| = |C_2| = |C_3| = 3$ with $o = 3$. The resulting number of stimuli is then $3 * 3 * 3 = 27$. In a latin square, of the overall given 27 profiles, just these 9 profiles are selected where each level of an attribute occurs exactly once with the level of another attribute. Such a reduced design is also referring to as *fractional factorial design*. To reduce a asymmetric design, where the cardinality among attributes is of different size, is more complicated and approaches are presented by Street, Burgess, and Louviere (2005) (for example, see the *Blackett and Burmann Design* (Plackett and Burman, 1946)).

Chapter 4

Game Theory and Mechanism Design

> Well, if the rules of the game force a bad strategy, maybe we shouldn't try to change strategies. Maybe we should try to change the game.
>
> Brian Christian, Tom Griffiths

Game theory as a mathematical discipline and modeling tool has a long history, and its foundations and advances have been the contributions of some of the most brilliant minds of the twentieth century. Game theory is the mathematical analysis of strategic decision situations among rational decision-makers (Holler, Illing, and Napel, 1991; Myerson, 1991). Such situations are characterized by outcomes of one decision-maker (or agent) that depends on the outcomes of other decision-makers (or agents), while each decision-maker is aware about that (Holler, Illing, and Napel, 1991). That way, game theory oftentimes analyses conflict situations with diverging agents' preferences. By means of game theory, complex coordination and decision situations can be modeled and solved mathematically with the help of mathematics, operations research, or economics.

While game theory deals with analysis of games, mechanism design is concerned with designing games with desirable outcomes (Narahari, 2014). As described by Narahari (2013), mechanism design can be viewed as *reverse engineering* of games or equivalently as the art of designing the rules of a game to achieve a specific desired outcome. While designing mechanisms, it is assumed to have selfish-acting agents given, i.e., each agent is interested in increasing its own utility or payout. More recently, game theory has been adopted by the disciplines of computer science and electrical engineering as part of many new applications (Narahari, 2014).

In game theory, the term *game* means that the involved decision makers (so-called agents in a game-theoretical sense) are assumed to be *rational* and *intelligent*. While *rational* means that the involved agents are interested in maximizing their own utility, *intelligent* means that they are capable to find their optimal strategy or type in order to maximize their own utility. While doing so, game theory provides a mathematical vocabulary and a set of notations to model specific situations where multiple self-interested and rational agents are involved.

4.1 Key Concepts

In the following, the key concepts of game theory are outlined. This presented key concepts come essentially from Narahari, 2014.

A *strategic form game* Γ is a tuple $(N, (S^i)_{i \in N}, (u^i)_{i \in N})$ where N is the set of agents involved in the game Γ, $S_1, \dots, S_n$ are sets of strategies of agents $i = 1, \dots, n$, respectively, and $u^i : S_1 \times \cdots \times S_n \rightarrow \mathbb{R}$ are the utility / payoff functions of agents $i = 1, \dots, n$.

Each agent has preferences over possible outcomes of the game Γ. Between the outcomes exist a reflexive, transitive, and complete preference relation. Since each agent is assumed to be rational, the preferred outcome is that one that has the highest utility for this agent – that way, the outcome is preferred. A utility itself does not only depend on the individual choice of one specific agent, but on the choices of all agents together. Against that background, being rational means that the agents are self-interested – interested in maximizing their own utility. The agents utility functions associate utility or payoff to possible outcomes, while a rational agent prefers that outcome that yields highest utility for itself. That does not necessarily means that agents care only about themselves, and it does not necessarily means that agents want to harm others – they just prefer outcomes that maximize their utility at the end.

The concept of intelligence is strongly related to the concept of common knowledge (also known as mutual knowledge). Common knowledge is knowledge that is shared across all agents. It follows the form "every agent knows that every agent knows that $\cdots$ every agent knows it" (Hild, Jeffrey, and Risse, 1997). Agents might further have private information, that does not belong to the common knowledge. Once the game is in it strategic form with complete information, every agent knows the set N, the strategies $S_1, \dots, S_n$, and the utility functions $u^i, \dots, u_n$. Games with incomplete information contains agents who have private information that do not belong the common knowledge, and possibly expectations about the utilities of others. Then there exist information asymmetries among the agents. The concept of intelligence then means that every agent is able to calculate its best response to the game – he knows it *best response strategy*.

Furthermore, games can be classified along categories. The most well-known categories are non-cooperative versus cooperative games, static versus dynamic games,

games with perfect information versus games with imperfect information, and complete versus incomplete information. The largest part of game theory focuses on non-cooperative games where self-interested, rational, and intelligent agents pursue strategies promising highest utility for them at the end. Cooperative game theory focuses on coalition or groups of agents. When all groups are are singletons, then a non-cooperative game emerges. The next category, static versus dynamic games, focuses on the timestamp agents choose their action. In a static game, all agents choose their actions simultaneously, while – in a dynamic game – actions are chosen with time between these actions. Such a game is also known as multi-stage game, since it consists usually of multiple rounds. When agents have information about the past rounds, this circumstance is called perfect information. That way, agents use their intelligence to incorporate past information to be able to find their best response strategy. Once a game deals with imperfect information, parts or the whole part of the history is unknown. Lastly, as already mentioned before, complete information refers to a situation when every agent knows everything about the others. Otherwise, the situation does have incomplete information and information asymmetries are given.

4.2 Mechanism Design

Mechanism design deals with situations where a group of selfish agents have private information (or preferences), these information (or preferences) are required to be announced to a superior social choice function to take a decision. The agents could announce (report, signal) untruthfully their information, in order to influence the final outcome with the goal to increase their own utilities. Put differently, the situation is characterized by information asymmetries, where agents have actual information that are not publicly known. In order to solve the decision problem at best, the agents must behave trustfully; otherwise the outcome is threatened to become worse. Since the agents are assumed to be selfish and rational, the individual rationality of one agent is confronted with the group individuality. This is also called a *social dilemma* or the *collective action problem* – because the agents do not cooperate, they act according to their strategies to benefit from maximal utility. Because sometimes higher utilities make strategic behavior necessary, deviations from truth are possible or, in a more game-theoretical sense, individual rational.

In a mechanism design environment (see Figure 4.1, consider that X is O), there are N agents given, namely $N = \{1, \ldots, n\}$, which act strategically among themselves towards making a collective decision. The collective decision leads to outcomes, which are denoted as O. Each agent has preferences about the outcomes X. The preferences are also called type. That way, the agents $i = 1, \ldots, n$ have actual / true preferences $\theta^i, \ldots, \theta^n$ over the outcomes X. But they might behave strategically and signal another type $\widehat{\theta^i}$ in order to increase their utility u^i. While differences between the announced type $\widehat{\theta^i}$ and the actual type θ^i for each agent i exist, all

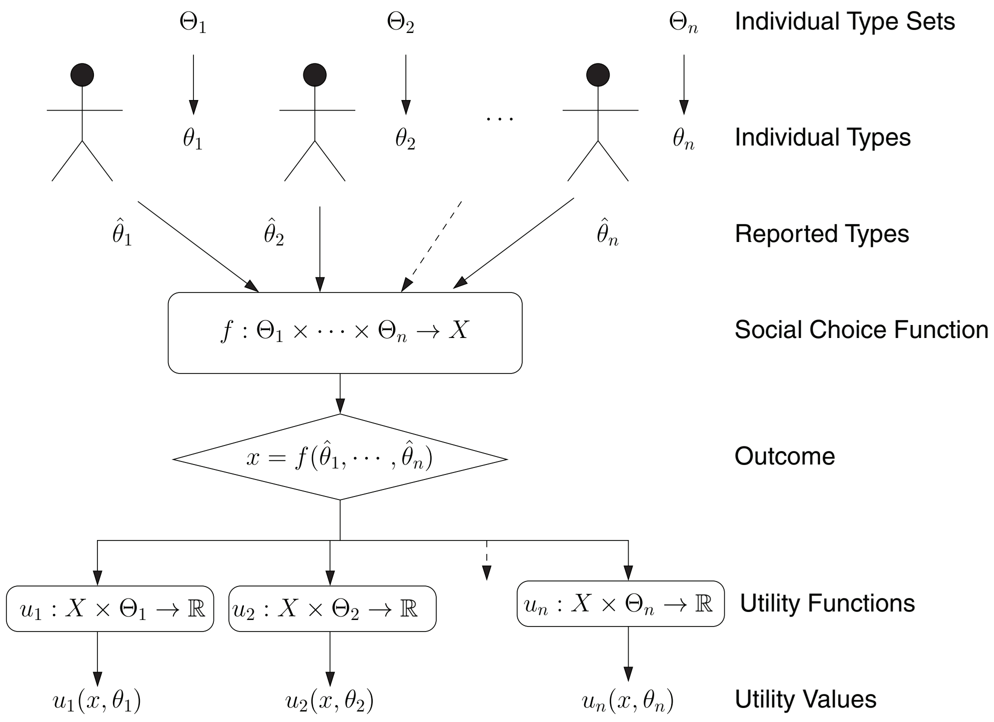

FIGURE 4.1: Mechanism design environment (Narahari, 2013)

types belong to a set $\theta^i, \widehat{\theta^i} \in \Theta^i$ (beyond this, Θ^i might contain further specific types, which is private information of agent i). All types across all agents are denoted by $\theta = (\theta^1, \ldots, \theta^n)$.

A social choice function $f : \Theta^1 \times \cdots \times \Theta^n \to X$ is a mapping of a type profile $\theta = (\theta^1, \ldots, \theta^n)$ to outcomes, such that each type profile is assigned an outcome $o \in O$. Finally, the agents have utility functions from which they derive their utility u^i. According to Narahari (2013) There are two problems to be solved: The first problem is the so-called preference elicitation problem that deals with the situation that the agents have private information and these private information are required to be elicited (also called the information revelation problem). The second problem is the preference aggregation problem, dealing with the situation to aggregate the elicited preferences into an outcome – based on the social choice function.

Part III

Engineering a Participatory Decision-Making System

Chapter 5

Reviewing the State of the Art of Distributed Ledger Technologies[1]

> The secret of getting ahead is getting started. The secret of getting started is breaking your complex overwhelming tasks into small manageable tasks, and then starting on the first one.
>
> Mark Twain

On the one hand, we have a gradually grown awareness and importance of sustainability and natural resources such as common-pool resources. On the other hand, DLT gains increasingly interest and may have ecological, economical, and social potential and possible impact that have not been completely examined so far. To present the state-of-the-art and hot topics at this, bioeconomy, natural resources, and DLT are reviewed equally and future research threads are outlined in order to answer the research question:

> **Research Question 1:** *How was or is the Distributed Ledger Technology (DLT) used in the field of bioeconomy, especially the field of forestry?*

While doing so, a systematic literature review procedure hybridized with text mining and a classification algorithm to enhance the data collection phase was conducted. Consequently, each of the resulting cluster describes a dedicated research thread. This work ends up with real-word and possibly future-potential implications driven by DLT. Overall, this review gives important insights on how DLT was and could be used to add value towards sustainability at bioeconomy, natural resources, especially common goods.

[1] An earlier version of this chapter has been published as Willrich et al. (2019)

5.1 Introduction

Bioeconomy brings natural resources (especially common goods) and economy together. It means being in exchange with natural resources in a sustainable and responsible way while using biological resources to undertake economic activities (McCormick and Kautto, 2013). While doing so, we consider scarce fossil natural resources and general implications towards the climate change. This kind of economy is trying to create a knowledge-based production and usage of natural resources with the goal of developing new products, procedures, and services in all economic branches, with the focus of providing a sustainable economy (Bioökonomierat, 2017). At the same time, with Corporate Social Responsibility (CSR) (Orlitzky, Schmidt, and Rynes, 2003) and corporate sustainability (Gómez and Medel-González, 2015), organizations are getting sensitized and are taking such thoughts into the design and distribution of products or services. Many researchers agree upon that the explicitly growing world population cannot continue on the way they are currently in exchange with natural resources and that new ways to behave commercially are sought after – just in the light of sustainability and ecological responsibility. Further, as time goes by, it gradually becomes more and more important to establish and to ensure a good governance to natural resources and bioeconomy (Devaney, Henchion, and Regan, 2017). Hence, the topic around bioeconomy is also touched politically, there are activities involved such as participation and citizen science. As bioeconomy normally includes a multitude of ecological, economic and social parties with his own interests, it is aligned to cross-industries and may consist of complex supply chains – in this connection, working together in a trustable and reliable way is wanted. Here, several autonomous organizations are encouraged to work together for a benefit what requires, e.g., activities like negotiations, coordination, contract-conclusions between these. On the other hand, since DLT is arising, there is a promising candidate to challenge uses cases where different autonomous parties (want to) work together and where trust could be (is) an obstacle. This way, neither intermediaries are required nor parties are enforced to trust somebody blindly in case of an association (Nguyen, 2016) as now several parties are able to get into business in a peer-to-peer topology. The DLT provides in distributed nodes whereby every node consists of a kind of history about all states being made alongside a given time and by means of a consensus mechanism, all nodes are synchronized. This is why parties can interact with each other while preventing each decision and transaction from tampering and transparency, availability, and reliability (no single point of failure) are inherently given. In this contribution, we present a structured literature review. In order to do it, we have applied a text mining approach (Yang and Hong, 2017; Yang, Zhang, and Yan, 2017) to the results we received by the most promising and topic-related search queries (went into breadth). This text mining approach was used to classify our literature automatically alongside the various priorities. Lastly, we discussed every auto-generated cluster separately and went into depth.

Characteristic	Category			
1 Focus	Resarch findings	Resarch methods	Theories	**Practices or applications**
2 Goal	Integration	Criticism	**Identification of central issues**	
3 Organization	Historical	**Conceptual**	Methodological	
4 Perspective	Neutral representation		**Exposure position**	
6 Coverage	Exhaustive	Exhaustive with selective citation	**Representative**	Central or pivotal

TABLE 5.1: Definition of research scope

5.2 Literature Review

The literature review is one of the basic steps to start research. In this paper, we want to analyze the state-of-the-art in the field of bioeconomy and DLT and suppose possible future research threads. To review the literature in a clear and structured way, we follow the guidelines from Webster and Watson (2002) and in particular use the approach of Brocke et al. (2009). This method is a framework organized in five phases. Each of the following sections represent one of these five phases.

To define the scope of our research, we use the taxonomy described by Cooper (1988). In Table 5.1, we highlight the categories helping define an appropriate scope of our research.

The focus (1) of our literature review is to find related practices and/or applications where Distributed Ledger Technologies aka blockchain in the field of bioeconomy were used or, if we do not recognize a wide variety appropriate to the intersection of our key words, finding the best and nearest literature being not far apart from these. Because the combination of bioeconomy / managing natural resources with the technology of distributed ledgers is not widely discussed, our goal (2) is to identify the central issues within this field. The structure of this review is organized (3) in a conceptual way. It is written with an espousal perspective (4) since we are convinced that distributed ledger technologies are not sufficiently examined, especially with respect to the context of bioeconomy, and a ledger with a distributed infrastructure could fit in the field of communal used natural resources. We address a specialized audience (5) with this review, because the terms and concepts, especially in the scope of DLT, need a deep understanding of cryptography, distributed databases, and knowledge about the patterns of communication within computer networks. Lastly, since we ask several academic databases with the same key words in a breadth-oriented search, the review reaches a representative coverage (6) of the topics.

5.3 Conceptualization of Topic

In this section, we describe the basic concepts and terms related to our review. The goal of the second phase (Brocke et al., 2009) is to put an overview about the contextual definitions needed to understand the basics of our research area and help us to find new keywords for our literature search. Further, the definitions provide an understanding by which we had conducted the literature search and possible synonyms were derived.

Bioeconomy is the knowledge-based production and usage of natural resources, to create new products, procedures, and services in all economic branches, with the focus of providing a sustainable economy (Bioökonomierat, 2017). Goals of bioeconomy are, e.g., to support the change from fossil fuels as the economic engine to an efficient economy based on renewable energy. To reach a secure and long-term supply of renewable resources to support a sustainable, efficient and resource saving usage, reliable circumstances must be given. In total, the topic spans from encouraging consumer to be part in a bioeconomy value chain of sustainable consumption until the protection of the climate (McCormick and Kautto, 2013). It embraces political and society topics alike, and range from participation and citizenship to democratic and liberation approaches. It has the claim to include each individual since each individual is affected by bioeconomy and natural resources.

The rise of DLT has most probably begun when Satoshi Nakamoto (a person or a group of people) had published his understanding of the blockchain technology in 2008 (Nakamoto, 2008). In this connection, blockchain can be understood as one potential implementation of a DLT (Cachin, 2016). In this work, we generally use DLT and blockchain interchangeable but prefer DLT. Both synonyms occur in this work because some of the examined literature uses blockchain instead of DLT. As conceptualized, the DLT potentials come from its distributed and decentralized structure – resulting in the missing necessity of any intermediary or any central unit. Since every technical, organizational, or human agent looking like an intermediary can be supposed to be a black box. Where trust can become a problem, DLT provides an alternative way to interact without the need of trust (Hawlitschek, Notheisen, and Teubner, 2018). Hence, intermediaries like lawyers, brokers, or bankers might no longer be a vital or indispensable part of transactions. Through its shared and transparent database and its consensus mechanisms, DLT enables transactions between different parties in a verifiable and permanent way. The transactions made are persistent in a transparent, immutable, and traceable way (Nakamoto, 2008) and consequently protected from deletion, tampering, and revision (Iansiti and Lakhani, 2017).

Furthermore, DLTs may have the ability to trigger transactions automatically. With that feature, referred to as Smart Contracts, DLTs are empowered to execute

Database	Blockchain	Bioeconomy (Merged)
IEEE	976	143
Elsevier	1605	13557
Springer	1297	5208
arXiv	312	19
Crossref	1522	1419
Distinct Total Count	4738	13804

TABLE 5.2: Results of the basic search field search

programs at specific (time) events (Buterin and Others, 2014). When time has come (or the event happens), the contract is executed.

5.4 Literature Search (Data Collection)

In this section, we document our literature search procedure. The research fields we target are relatively new, that is why we do not set any boundaries such as specific journals or conferences. At the end of this section and with this information in mind, we want to identify journals and conferences that cover our research topics DLT and bioeconomy most suitable.

For the field of bioeconomy, several synonyms are existing while each meaning slightly differ. Therefore, we have used the three most common terms for our "bioeconomy" keyword search, i.e., bioeconomy, bioeconomics, bioeconomic. In addition, DLT is not widely used in publications, mostly the authors refer to blockchain and use this term as the generalized name for the technology. As a result, our first search terms were (blockchain AND (bioeconomy OR bioeconomics OR bioeconomic)).

In behalf of a comprehensive understanding our data collection phase, we briefly explain the procedure in more detail: We used a self-programmed tool that calls the application programming interfaces (short APIs) of different research databases. That is, IEEE, Springer Link, Elsevier, Crossref, arXiv as they provide a convenient way to receive machine-readable data for further analyses. The process of harvesting the data was conducted in three steps. In the first step, search request were sent to the mentioned APIs. After it, in the second step the harvested data got cleansing, which consists of identifying and cleaning up duplicates, removing papers not written in English (for better text mining results), and information aggregation due to different results emerged by different databases for the same publication.

Our literature search has been conducted from May to July of 2018. Table 5.2 shows the count of literature given back from each databases for the query introduced before.

An iterative process has led to an optimized query yielding meaningful results with respect to our research area, e.g., our first trial had led to deep biology research that are generally out of the scope of our review. The final search phrases to build our document corpus are the following, with the count of results per search query in brackets.

Blockchain Democracy (5.879), Blockchain Government (11.010), Blockchain Sustainability (10.188), Blockchain (4.738), DAO (19.549), DLT (21.249), Natural Resource Blockchain (13.109)

5.5 Literature Analysis and Synthesis

This section describes how we have analyzed the meta data of our publication dataset and shows up some data insights. While doing so, with Figure 5.1, we depict an overview about the publication rate over time in research for these topics. The next step in our analysis is to cluster the publications with basic algorithms of natural language processing (NLP) (Manning and Schütze, 1999). To go more into detail, we have used the abstracts and titles to build a bag of words corpus where we, as usual in NLP, have removed common and field specific stop words, and stemmed the sentences to tokens. After that, we have calculated the Term Frequency – Inversed Document Frequency (TF-IDF). Next, to find overlapping research fields and to identify often-covered fields within our topics, we have clustered the TF-IDF of each document. This procedure is partly based on an existing contribution on how performing literature review by text mining (Yang and Hong, 2017; Yang, Zhang, and Yan, 2017). To conduct our clustering, we have applied K-Means to identify groups in our dataset. To determine the optimal number of clusters, we have used the common method in unsupervised learning, the elbow method. To find the best k, we have calculated the distortion score (sum of squared errors) for a different number of k, in our case 1-10, as we have sought for the smallest k with a low score. Finally, after we have reached our clusters, we have classified them manually based on the top terms.

The analysis of the date of publication for each data record of the two basic search queries is displayed in Figure 5.1. This chart gives insights that the research field around blockchain technology and bioeconomy is continuously rising in the past years. Bitcoin (and therefore the blockchain) was developed in 2009, but there are not any publications before 2014 while bioeconomy has been a research objective for over the last decades. The publication date analysis makes visible that since 2007 the count of released publications is becoming more popular, with the exception of the not yet ended year 2018. This explains that this topic is also becoming more relevant in research in the recent years. The analysis of the container type shows us that there are already popular conferences and workshops explicitly concerned to DLTs and blockchains, although it is only one decade old, there are already 200 papers each year since 2016 and over 1500 each year since 2017. In fact, the "Journal of Bioeconomics" is the most popular under all containers in the field of bioeconomy.

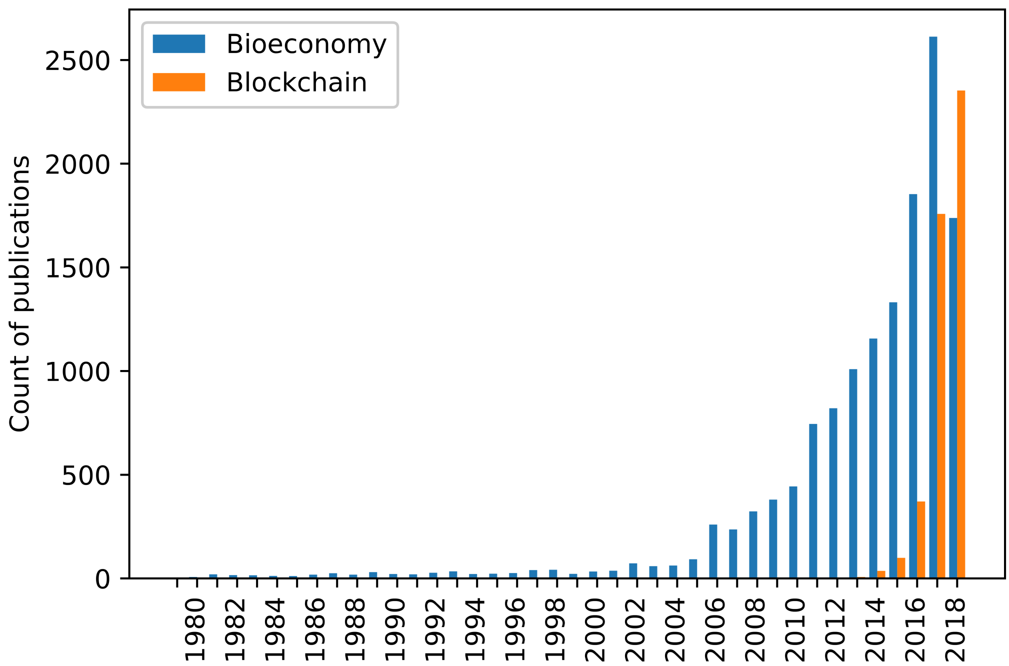

FIGURE 5.1: Publications per year

The following sections are descriptions for each of the four clusters the k-means algorithm has calculated, with the given TF-IDF matrix of our document corpus. The TF-IDF matrix is the basis for our clustering and contains all of tri-gram tokens in our corpus. We reduced the corpus size before the clustering by filtering out all data records without an abstract and with less than two citations. The results of the cluster analysis can be found in a GitHub repository [2].

Supply Chain Management. One of the calculated clusters is linked to publications about possible DLT use cases in the Supply Chain Management (SCM) sector. The SCM is an often-discussed application type in the field of Distributed Ledgers (Iansiti and Lakhani, 2017). A supply chain is a tool to determine the origin of a physical good, to track its way from the provenance to the consumer. On this transport way, it is useful to identify the actors who are involved in (Toyoda et al., 2017) to optimize the entire value chain. The rise of a connected industry i.e. through the Internet of the Things (IoT) takes a supporting role in a digital SCM (Haddud et al., 2017; Kshetri, 2018), many products are equipped with RFID and/or are monitored with sensors, and this makes it possible to track the product. The analysis of these papers shows us, that there are different problems where a blockchain based supply chain could be a solution. In a globalized world of international trades and multi organizational supply chains, a system to ensure security, integrity and provenance is necessary to identify counterfeiting products. One information a RFID can contain

[2]https://github.com/melcherf/literature-review_bioeconomy-blockchain (commit id: 64bf59d9dccf980f6b873e96b04510e914e3f916)

is the identity of the manufacturer, to transport the information to the next party in the supply chain. We analyzed a papers who are engaging in the subject of real-time information sharing during the distribution phase of a product (Nakasumi, 2017). The goals are on the one hand the optimization of the workflows, and on the other hand to increase the transparency between the parties. However, at the end of the supply chain their genuineness is no longer guaranteed, because the digital identity tag can be cloned and then be used to tag counterfeit products. To secure the post supply chain some IEEE members (Toyoda et al., 2017) proposed a Product Ownership Management System (POMS) based on a distributed ledger. Martin Holland et al. describe a blockchain based digital rights management system to secure the copyrights of, especially safety-critical, products (Holland, Nigischer, and Stjepandic, 2017).

Another example to avoid counterfeiting is a design described in (Mackey and Nayyar, 2017) including a blockchain to fight against an international fake medicine market. A more complex analysis of the healthcare market and the possible adoption of the DLT is described in (Clauson et al., 2018). Another industry where one big problem is the safety and quality of a product and not in the first place the copying is the agriculture industry. Feng Tian (Feng Tian, 2016) addresses the agrifood supply chain in Chinas constantly growing economy. They developed a system, which covers the whole process of information retrieval and management in a agrifood supply chain, which includes the monitoring, tracing and traceability management for the quality and safety "from farm to fork" (Feng Tian, 2016). That quality of a product is an important factor shows the paper (CHEN and LIU, 2017). They argue that China loses every year 170 billion Renminbi (RMB) in the agriculture industry because of quality problems and losses in supply chains (CHEN and LIU, 2017). They developed a theoretical framework and a system architecture to avoid problems that traditional centralized trust mechanism in a supply chain cannot solve, the distrust in unchanged information between two suppliers. Their paper for example describes an automatic execution of quality management contracts to monitor the process and quality during the production steps.

While looking at supply chain management, the blockchain was not only used in the domain of tracking physical goods, a significant part of these use cases refer to the management of energy. Also following the decentralized idea, with microgrid energy markets (Mengelkamp et al., 2018a), the trading between self-producer (i.e., prosumers) and consumer in a peer-to-peer network is understood where the need for an intermediate entity is explicitly excluded (Mengelkamp et al., 2018b). However, how the communication between partners in a peer-to-peer network could be expected to be compatible with security and privacy efforts are shown and exemplified on smart grids (Zhumabekuly Aitzhan and Svetinovic, 2016). When the blockchain technology is used to support coordination and hence needs communication, such thoughts are crucial – especially when such solutions raise the claim to be practice-conform.

To build the bridge between bioeconomy and blockchain from the energy application's point of view, the blockchain is effectively applicable whenever the existence for central actors should be vanished. If we argue from the natural resource management perspective of the forest, it is desirable to merge small forests together. This causes the emergence of small forests to be a forest association being planned to be reached in Germany (Bundesministerium für Ernährung und Landwirtschaft (BMEL), 2008). This way, decentralized coordination purposes with partners on eye level can leverage the emergence of such associations in a transparent and efficient way. In this case, there are several similarities to other scarce resources such as energy, i.e., such concepts might give already first insights of how the blockchain could be used in bioeconomy. Another part of an effective Bioeconomy is the transparency and traceability of the products. Therefore, that anybody can be sure, that the physical good he is consuming, coming from an eco-friendly producer. That's not only important for the consumer, the next actor in a supply chain can be sure he is processing products that meet his quality standards, for example to receive an environmental certificate. In this regard, the lessons learned from the SCM research items are of high interest for a bioeconomy.

Blockchain Protocol. The biggest part of the document corpus was assigned to a cluster with the general topic of the blockchain protocol, mainly focused on the Bitcoin design, outlining the fields of security, privacy, smart contracts, the decentralized architecture and possible on chain applications. A broad coverage of aspects relevant in research and production about blockchain gives the paper from Joseph Bonneau et al. (Bonneau et al., 2015). In a historical overview, they describe the origin of the first cryptocurrencies with blindly signed coins and companies trying to launch an electronic cash system. They also give an exhaustive technical overview about the Bitcoin design decisions including the Bitcoin Improvement Proposals (BIPs), developer mailing lists, wiki articles and so on, trying to cover the current specifications, which has continuously refined since the release of the original Bitcoin white paper (Nakamoto, 2008). A selection of the specifications they describe are the transactions, consensus, block confirmation, (incentivized) mining and the impact on the consensus. They also analyzed the stability of the Bitcoin protocol, with five stability properties, and they say that the protocol is stable if all of these properties hold (Decker and Wattenhofer, 2013). Further, in this paper the client-side security, anonymity, the modification of the protocol and the alternative consensus algorithm are discussed. The work by Bonneau et al. is highly recommendable to get a widely overview about the Bitcoin protocol. In a more on the peer-to-peer network focused paper (Decker and Wattenhofer, 2013) the information propagation between the nodes is researched. Decker and Wattenhofer investigated the methods used to broadcast the transactions and blocks through the network and verify the aspect that a delay in this broadcasting method could result in a fork of the blockchain.

A fork is a split of the blockchain in two separated ledgers with the same history but a different protocol for the future and is mostly unintended.

Researchers address possible blockchain improvements and emphasize several challenges towards architectural limitations. Non-determinism might be a problem. Smart contracts are decentralized applications that are applicable in several domains, e.g., crowdfunding, financial services, identity management, and gambling. It touches topics like cryptography, consensus algorithms, programming languages until governance, finance, and law (Buterin and Others, 2014). With the transparent nature of a public blockchain, all transactions including money flows and transaction amounts are exposed but sometimes unwanted. To now use the benefits of blockchain and to ensure privacy simultaneously, a cryptographic protocol allow programmers to write private smart contracts in an intuitive manner (Kosba et al., 2016) and without knowledge in respect to how implement cryptography. Further research concentrates on how making smart contracts to be smarter. When considering Ethereum's smart contracts, it can be seen that a high degree of adoption with an enormous amount of contracts and millions of dollars exist. Hence, the security of running smart contracts was investigated. To make possible manipulation potentials transparent and clear, they have revealed security problems that may be utilized by adversaries to gain profit and have argued how such vulnerabilities could be reduced to make more security possible (Luu et al., 2016). One task is to enhance the security within smart contracts, another task to give more security on how data gets into smart contracts. Concerning this matter, thoughts have given to trustworthy data feeds acting as bridge between blockchain and non-blockchain applications. Following this, a blockchain application to ask HTTPS-enabled websites was developed and serves as a source-authenticated data to relying smart contracts (Zhang et al., 2016).

Moreover, when talking about applications of blockchain and smart contracts, (no) trust is a crucial driver. Whenever collaboration, coordination or cooperation across organizations is intended without having trust given by neither a central authority nor any participant, decentralized approaches with consensus mechanism work for a relying and secure infrastructure shaping the basis for such associations. Not just offline existing parties may be involved, but also digital ones, i.e., a decentralized autonomous organization (abbreviated DAO) (Luu et al., 2016). DAOs are organizations based on smart contracts (Swan, 2015c). When such DAOs are organized in business networks, cross organization collaboration gets possible (Norta, 2016). To take decisions in those organizations democratically, mechanisms to organize and conduct votes or elections are required, thus another research stream tackles voting or elections realized by dedicated blockchains or smart contracts (Yavuz et al., 2018). To handle a digital organization adequately, every-day or strategic decisions are required in a recurring manner. On the question of how such voting systems are possible, a simple implementation is made (Yavuz et al., 2018).

Bioeconomy's challenges can be addressed by these findings. As already introduced, the topic of bioeconomy imply the involvement of a multitude of various parties working together in, i.e., supply chains or associations where previously independent organizations are merged. Smart Contracts may help to set up an (decentralized autonomous) organization, to organize it and to make processes / decisions more efficient and time-saving, and to benefit from collaboration. In addition, according to garbage in, garbage out, contributions to differences between physical entities and digital twins can be utilized and applied to (physical existing) natural resources.

Governance. With governance, the process of governing is meant (Bevir, 2012). To manage (social) systems and / or organizations, we undertake several tasks to hold it healthy and make it work. In literature, the implications of blockchain and governance are discussed, i.e., how owners and managers of public companies are affected during tasks around corporate governance (Yermack, 2017). In this way, blockchain implications range from technical to economic and strategic areas and may trigger a need for institutional changes where operative and organizational processes may be affected. For example, the information stewardship changes while data is stored in the blockchain (Ølnes, Ubacht, and Janssen, 2017), apart from that it faces corruption and wrongdoing perpetrated by frauds (Souza, Luciano, and Wiedenhöft, 2018) through the aid of transparency, immutability, and traceability. To understand blockchain not just as a technology enabler, but also as a possible next step towards institutional evolution, decentralized, democratic, and self-organized ideas come in (Davidson, De Filippi, and Potts, 2018). For example, banking is one of the most popular domains in that blockchain-driven disruptions arise, including how banks work as organizations too, i.e., such a conventional and centralized hierarchical organization is discussed to be shifted into those democratic, decentralized, and self-organized ones (MacDonald, Allen, and Potts, 2016). When considering social and society aspects while discussing governance, various governance models can be taken into account, hereof researchers have examined the interaction between blockchain and social contract theories for example (Reijers, O'Brolcháin, and Haynes, 2016). Another example was given by a Libertarien viewpoint with its remarkable resemblance to blockchain properties as both bypass central authority and provide anonymity (Huckle and White, 2016), but coordination and reaching consensus could become more complex (Shermin, 2017).

Bioeconomy may benefit from those blockchain-driven developments as it also affects participation, citizen science, governance, cross-industrial areas, and supply chain management. Especially natural resources touch every individual alike and are hence worth considering in a democratic and representative way.

Decentralized Networks. This chapter deals with the papers in the cluster about mulit-agent systems (MAS), the self-organization of vehicles and robotic automation of processes, which also includes the protocols to gather the information recorded by wireless sensor-networks. In a vision of the future, intelligent agents will do processes in an effective bioeconomy. Multi-agent systems are often referred to as a self-organized system; there are many similarities between a blockchain and multi--agent-system. To mention one, they both need a distributed consensus algorithm to ensure the integrity of the data send between the nodes or agents (Olfati-Saber, Fax, and Murray, 2007). One popular paper we discovered within this cluster is about a theoretical framework to analyze consensus algorithms in MAS with fixed or dynamic network topology (Olfati-Saber, Fax, and Murray, 2007). The scope of the framework is about the information flow, the robustness when network nodes fail, delays in time and shows the possible guarantee of performance in MAS with different consensus algorithms. Another interesting paper about automation is by Willke et al. (Willke, Tientrakool, and Maxemchuk, 2009), they surveyed inter-vehicle communication (IVC) protocols and applications of the last decade and classified them into four types: General, safety, group planning and individual planning & regulation. These applications and protocols are used in traffic control, vehicle formation, coordinated braking and so on. They also depend on consensus algorithms in decentralized networks and a fast propagation of information. Consensus algorithms for a decentralized control of communicating-agent systems are discussed and analyzed in the work of Xie and Wang ("Consensus Control for a class of Networks of Dynamic Agents: Fixed Topology"). Furthermore, the connectivity and coverage in wireless sensor networks and the impact on the quality of service is discussed. These networks are used in the military, industry, agriculture, urban management and other fields (Zhu et al., 2012). In their work, they examine current research results, solutions and current problems with an eye on the energy efficiency. To ensure the authenticity and integrity of the data gathered by these sensors a blockchain could be a possible solution. In our research field, MAS as well as wireless sensor networks and the automation of processes could have a huge impact on the development of an autonomous organized forestry.

5.6 Research Agenda

In our structured literature review, we have examined the state-of-the-art and most cited literature towards the concepts of bioeconomy and DLT found with our keyword-driven approach. All in one, we have identified several dedicated research threads by our clustering approach. After it, we described each separately and conclude each with relevant implications between bioeconomy challenges and DLT solutions. Since there was no cluster dedicated explicitly to bioeconomy and DLT, it seems worth to higher research efforts in this domain to reveal possibly relevant knowledge gains and to close research gaps. This could include topics around participation over Distributed Ledger Technologies. Literature have further focused on supply chain management, government, and application development with DLT's smart contracts on public domains or where companies come together to work in an association with no longer need for an intermediate who acts in the middle between different parties with diverging interests. Especially the topic around supply chain management and government with DLT arises as a promising candidate to enhance bioeconomy-oriented activities since transparency, immutability and – in general – the benefits of digitalization are driver to revolutionize collaborative tasks. Besides this, governmental tasks in the field of blockchain are closely connected to topics such as participation and decentralized, participatory decision-making among parties having diverging preferences in mind. When we look at resource management, many efforts have flowed into energy tasks such as Energy Internet and so forth, but natural and renewable resources such as wood have not been an objective of research so far. Again, since today's usages of DLT also reach to voting mechanisms and partly usages within elections, DLT could be positioned in the field of participation and SW among all those who are participating. This could lead to a more societal management of common goods.

As for all publications to blockchain, it is also true here that DLT is not the solution for all problems we are currently facing and a requirement-driven approach is advisable. Despite the benefits of DLT, the underlying question is related to trust (Beck et al., 2016), i.e., is there any trust problem justifying the DLT application or can we meet our requirements with a central and trustable party too? Anyway, based on the review's findings and the contemporary challenges in the field of bioeconomy and natural resource, DLT and its beneficial features are worth considering. Especially when taking into account that DLT is a relatively young technology and scientifically not yet examined completely and thus the offer, the potential and impacts is not sufficiently clear.

Therefore, further research may address the whole system bioeconomy is embraced by. In particular, this includes the society and all relevant stakeholder in and socialize the process of natural resources decision-making by an appropriate DLT design. Care for transparency on society-affecting decisions and provide a basis for natural resource governance in a democratic manner and for the benefit of climate and according to the Sustainable Development Goals (SDGs) (Group et al., 2015).

5.7 Summary

By giving this research review, we have made a contribution embracing two high--rated and important topics, i.e., to what extent have researchers examined how DLT can support sustainability towards natural resources and common goods within the bioeconomy. In order to approach the topic, we have conducted a systematic review by hybridization of the proposed literature review process (Brocke et al., 2009) and state-of-the-art text mining procedures to receive cluster to be examined. We argue for this methodology as it allows reaching the cluster emergence automatically and enables us to divide the whole topic into dedicated areas that we have called research threads – all of these in a deterministic, replicable, and justified way. We have described each cluster by reviewing the state-of-the-art (backwards) and with discussion of possible implications, potentials and challenges in the field of bioeconomy and blockchain (forward).

Further, our literature review demonstrates that both bioeconomy and DLT in combination are a promising candidate to become an emerging interdisciplinary research field. This anticipation is mainly driven by the challenges the bioeocnomy is contemporary faced with and the solutions a DLT provides – this review shows a growing activity and attention in both of them fields.

Chapter 6

Conceptualizing a Participatory Decision-Making System Using Distributed Ledger Technology[3]

> Without change there is no innovation, creativity, or incentive for improvement. Those who initiate change will have a better opportunity to manage the change that is inevitable.
>
> William Pollard

The emergence of DLT, especially developments known as blockchain 3.0, offers new possibilities on how to decide collectively decisions. DLT enables multiple people to take decisions in a collectively manner, without require them to have trust to other decision-makers nor require them to have trust to any intermediary (the approach of DLT is to make intermediaries avoidable and to shift the decision power completely into a decentralized structure - instead of hierarchical structures). So far, this research can be positioned in the field of participatory decision-making with DLT, and focuses on the use case of common goods, especially illustrated on the forest (or forest policy). The forest is a high-potential area for many people, provides valuable services to the climate, is profoundly important for sustainability with respect to resources, biodiversity, and so forth. In contrast, today's forests are frequently managed in a top-down organizational flow where some people are involved in decision-making whilst others remain uninvolved but still affected by. This leads to the research question:

> **Research Question 2:** *How needs a DLT-based Participatory Decision-Making System (PDMS) be conceptualized to fulfil participation requirements?*

[3]An earlier version of this chapter has been published as Willrich, Melcher, and Weinhardt (2019)

Meanwhile, the process of digital transformation takes place in almost any realm and shows up new ways of participation and of how people can secure their interests. Research objective is therefore to design a DLT-based system, i.e., a - in this work named - Participatory Decision-Making System (PDMS) where participation and DLT-based decision-making are brought together. Against this background, the current forest management situation in Germany is taken into account and the DLT is introduced as a potential enabler for a participatory decision-making of the forest, as a representative for a Common-Pool Resource (CPR). At the end of this section, economic potentials and incentives for forest owners are discussed – adoption is closely linked to acceptance of such models.

6.1 Introduction

The forest is a complex system with several functions for different stakeholders as it has a high importance in the endeavor of reaching climate goals, e.g., it absorbs billions of CO2 globally every year (Canadell and Raupach, 2008) and plays an important role for the preservation of biodiversity. Meanwhile, the forest is a place for leisure and recreation for people (a recreational function). Furthermore, it provides additional services, e.g., timber supply (productive function). While recreational and productive functions increase the intensity of intervention (because exploiting the forest's productive function is in conflict to nature protection), the protection function focuses on maintenance of, for example, biodiversity, tree species composition, nature protection measures and so forth (Herbert and Kant, 2010). Overall, these functions address crucial economic, ecologic, and social value (Ní Dhubháin et al., 2007; Karppinen, 1998).

Next, precisely these functions are those that are requested by different stakeholders – depending on their interests and their appropriate power of self-assertion. This is why forest management can be modeled as a multi-objective optimization problem where the weights are set depending on the individual utility functions for the participating stakeholders. In this process, stakeholders are involved in and affected by forest decisions. In the end, the forest is a source of natural resources to deliver raw wood, otherwise the society should benefit by its health – therefore a sustainable forest management is in everyone's interest (Food and Agriculture Organization (FAO), 2006) and a balanced management is of importance.

Consequently, we argue that especially the forest as a Common-Pool Resource (CPR) might be a suitable candidate of being governed in a participatory manner instead of a single person or institution. From this point of view, our aim is to sketch a forest management vision for the future where stakeholders have the ability to participate in co-decision-making. In order to achieve this, we first introduce our use case where we describe the current situation in Germany. Further, we introduce related concepts of decentralized decision-making. Especially the DLT is discussed as a candidate that might be able to tackle such challenges arising when participatory-driven decision-making across multiple stakeholders is sought-after. To support our DLT approach, we argue with the aid of a process of Wust and Gervais (2018) helping us to answer the question if a DLT makes sense or not. After this, we present a PDMS approach using DLT and highlight managerial / business opportunities and incentives to adopt such an approach.

First, Participatory management (Guyot, 2012) is discussed that is not new and already broadly examined in the context of management of CPR (Reed et al., 2009), including the way how stakeholders are to be identified (Reed, 2008). This reasoning is also supported by the principle 10 of the Rio declaration on environment and development (McAllister, 1992):

"Environmental issues are best handled with the participation of all concerned citizens, at the relevant level. At the national level, each individual shall have appropriate access to information concerning the environment that is held by public authorities, including information on hazardous materials and activities in their communities, and the opportunity to participate in decision-making processes. States shall facilitate and encourage public awareness and participation by making information widely available. Effective access to judicial and administrative proceedings, including redress and remedy, shall be provided."

Furthermore, participatory management is closely linked to participatory decision-making and the relationship to satisfaction and performance of decisions are examined (Black and Gregersen, 1997). Nevertheless, participatory management is frequently discussed in terms of an organization instead of a public good, CPR, or a natural resource in general. For example, the Tanzanian government had applied participatory management for a long time and researched participatory and non-PDMS in over three case studies where community involvement seemed to be correlated with improving forest conditions (Blomley et al., 2008).

The Forest in Germany

We describe the situation in Germany and want to motivate the suitability and importance for this approach, since current stakeholders are involved in and partly affected by contemporary forestry decisions. Therefore, the situation in Germany is the starting point and might be applicable to other country's situations.

To illustrate this use case, we focus on small private forest owners in Germany and support our reasoning by relevant facts (UNIQUE forestry and land use GmbH, 2018): In Germany are 1.1 million people employed within the field forest and wood. The annual revenue is 180 billion Euro. In contrast to other countries, Germany is one of the largest exporting nation for wood and wood-products. A detailed report of the forest inventory of Germany is updated every ten years. The data from 2012 are showing that about 1/3 of Germany is filled by forest, which is equivalent to about 11 billion hectare (almost the half is held by private owners). The question of how to farm a forest is highly important. Next, with the growing awareness of sustainability, an ecological viewpoint is required. In the certification of sustainably farmed forest, Germany is a leading nation worldwide (Bundesministerium für Ernährung und Landwirtschaft (BMEL), 2008).

Although this seems quite good, it is frequently highlighted that numerous potentials are not yet exploited to its maximum. As already mentioned above, there are many private forest owners. The number of small forest owners (less than 20 hectares) is estimated at 2 billion (UNIQUE forestry and land use GmbH, 2018). In this context, potentials relating raw wood or wood reserve within small forests are assumed to be existing. Utilizing potentials allow for a more sustainable usage of a forest; consequently and among others, this may reduce dependencies on import wood, reduction of atomic power or to slow down climate change. These potentials are based, for instance, on unused wood caused by absent mobilization of wood or other objectives private forest owners are pursuing. This includes that forest owners have their own ambitions, which might contradict with the common good (UNIQUE forestry and land use GmbH, 2018). Thus, on the one hand, forest owners have main jobs apart the forest domain and the forest potentials are not utilized completely (Bundesministerium für Ernährung und Landwirtschaft (BMEL), 2008). On the other hand, a multitude of stakeholders such as hikers or environmentalists have desires that are not met.

6.2 Towards Participatory Decision-Making

While such conflicting interests exist, we do not propose an approach to dissolve such conflicts but rather to allow participation and give the ability to exercise one's voting right. Following a set of participation requirements (Shepherd and Bowler, 1997), we derived a subset of those required to be satisfied when participation should happen in a fair manner (Innes and Booher, 2004):

Requirement 1: Since every stakeholder needs voice in order to co-decide, the entrance must be open for everyone. No access restrictions for everyone. *Requirement 2*: Since every stakeholder must rely on the condition that his or her voice will be given a fair consideration, the voice aggregation procedure must be tamper-proof and in accordance with the stakeholder preferences. *Requirement 3*: Since every stakeholder has to be able to see any activity, transparency across all proposals and decisions need to be guaranteed. *Requirement 4*: Since every participating stakeholder has own interests and the activities and decisions are made with respect to a public good (the forest) with social and ecological implications, the overall process should be conducted in a transparent and secured manner. Since we follow a requirement-driven approach and to satisfy these requirements, we propose an approach based on DLT that is justified by a comparison between mentioned requirements and DLT features.

With requirements R1, R2, R3, R4 at hand, we propose a DLT-driven approach for decentralized governance (Jentzsch, 2016a) where participatory features (Ølnes, Ubacht, and Janssen, 2017) are implemented, especially the ability to participatory decision-making. That way, DLT is no longer just a cryptocurrency but nowadays applicable to so much more use cases, e.g. governance is gaining more and more attention in the Information Systems (IS) literature (Beck et al., 2016; Böhme et al., 2015).

For this purpose, an broad introduction to DLT is given in Chapter 2 where the the rise and today's use of DLT is explained, e.g., how participatory governance meets DLT (Reijers, O'Brolcháin, and Haynes, 2016). We argue that this approach can be a promising candidate for satisfying participatory requirement while taking into account the concept of DAO – for instance implemented within the Ethereum protocol (Jentzsch, 2016a).

How the Requirements Justify a Distributed Ledger Technology

The topic around DLT might be regarded as a hype (Carson et al., 2018), this is why we argue very carefully. This is why it highly advisable for us to justify our decision to think the DLT together with participatory forest decision-making.

Our mentioned requirements for a PDMS vision are given on the one hand. On the other hand, we have DLT features that might be required. Anyway, if they are held to be required, they definitely yield a higher system complexity. To support our argument for the application of a DLT approach, we gradually go through a process that helps answer if a DLT is advisable for getting applied. This process is conducted and closely linked to our requirements R1 – R4 and takes DLT properties into account such as public verifiability, transparency, privacy, integrity, redundancy, and trust anchor. The following questions are part of the decision process (Wust and Gervais, 2018).

As depicted in Figure 6.1, the first question is: (1) *Do you need to store state?* Since the DLT stores both, the forest state data and the history of participatory-driven decisions, we answer the question with yes (satisfying requirement 3). (2) *Are there multiple writers?* Since multiple stakeholders are involved in taking part in co-decision-making, we answer this question with yes. (3) *Can you use an always online TTP?* A party that has trust of those involved. Indeed, this question is hard to answer. Our first assumption is that the participants (the stakeholder) have own interests and objectives – hence at least incentives exist to manipulate or tamper upcoming data in an (un)intentionally way. Our second assumption is that a participatory-driven forest management system of a public good should not be assigned to the responsibility of one single party (satisfying requirement 2 and 4). Therefore, the answer to this question is no; no always online TTP can be used. The next question is: (4) *Are all writers known?* Due to the openness of the forest and, consequently, the system, the answer

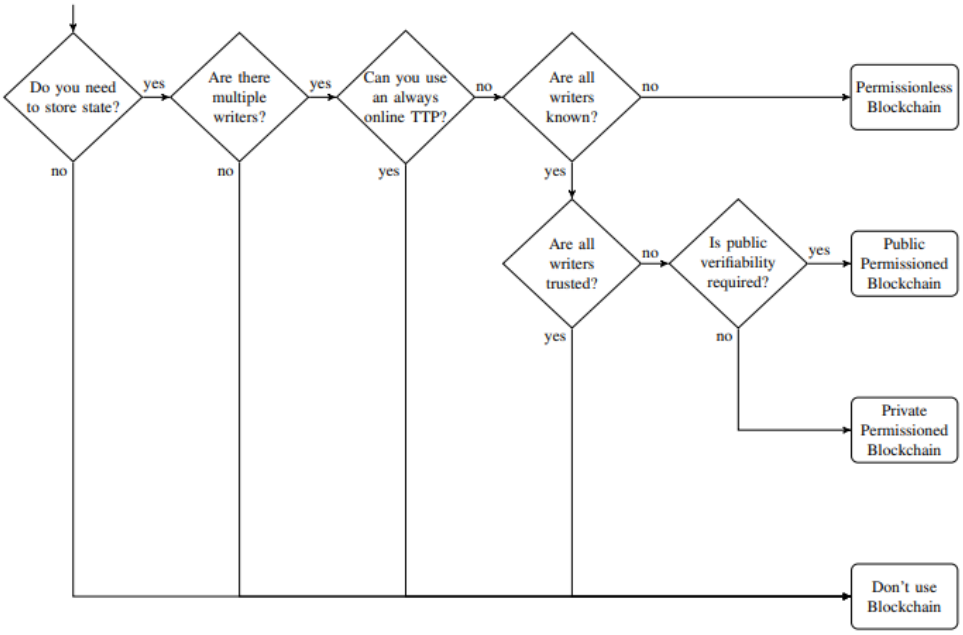

FIGURE 6.1: Decision process whether a Distributed Ledger Technology is an appropriate solution (Wust and Gervais, 2018)

is no. Potentially every stakeholder can decide to become part of the system and henceforth in the co-decision-making (satisfying requirement 1). The structure can be designed in such a way that every stakeholder is able to participate and access is not restricted to anybody.

According the proposed process, the recommendation is that a permissionless DLT can be a technical solution. Taking this into consideration, we sketch a participatory and DLT-based governance approach for a visionary forest management alternative.

6.3 A Participatory Decision-Making System

We describe a Participatory Decision-Making System for the forestry as management approach enabling stakeholders to co-decide while the forest owner dispenses from its right to decide solely. At this, a stakeholder can put his preference into a superordinated co-decision-making process, which is embedded in a PDMS, see Figure 6.2.

The Life Cycle Process

The PDMS is modeled according to the Business Process Model and Notation (BPMN), where we differentiate between three stages: (1) a construction phase that acts as long as the start-up continues and which embraces all nodes until the state Tokens emitted. Afterwards, (2) an operational phase that acts while the system is running and spans until the shareholders decide against its further existence (after the event

Voting finished). For the sake of completeness, the life cycle (3) ends with a deconstruction phase.

First, the PDMS is non-initialized. The process starts with the willingness of the forest owner to adopt a PDMS. Hereafter, the *construction phase (1)* initializes the state of the forest by inserting the forest inventory data into the DLT (in the following Forest State Database (FSDB) and in Figure 6.2 depicted as *Forest State Data*). Next, a *Forest Invariant (FI)* is derived. We use the FI to describe a desired state of the forest. The data stored in the (FSDB) has to fulfil the conditions of the FI. The FI is satisfied as long as the described state is fulfilled by the forest. The real data is stored and maintained in the FSDB, i.e., while the FI contains specific values representing the state of the forest, the FI describes the valid value ranges which FI data has to fulfil. The invariant is a describing ruleset that, for instance, consists of basal area (a factor indicating the timber stocks) or the amount of timber for energy purposes. Those condition attributes describe the desired real-word state of the forest and have to be compared periodically. In the participatory process, the shareholders have to exercise their voting right to agree on conditions. The initial value for the FI is derived by the current state of the forest. After the construction phase has finished, the FI is satisfied. However, as time passes, the forest is changing by deforestation, forestation or other natural and non-natural affecting activities.

In the last activity of the construction phase, with *Start ICO* the Initial Coin Offering (ICO) is conducted, i.e., every stakeholder has the opportunity to buy or sell shares (tokens in a DLT meaning) and hence to gain voice to co-decide. Once a certain amount of shares has been emitted, the construction phase ends with the event Tokens emitted.

The next nodes focus on the running system, the *operational phase (2)*. The first node is an event and indicates that the forest satisfies the FI condition. Whenever an event occurs, the *Receive event* activity catches the signal and propagates the flow further. An event can be stimulated by shareholders endeavors or by forest changes. Shareholders might express wishes towards the forest and trigger polls by proposing a topic to which every shareholder can vote - a voting phase is conducted and finished by the *Voting finished* event. In the invariant change co-decided flow, every voting has a result possibly affecting the FI, i.e., that means the shareholders can collectively co-decide on the FI. Afterwards, the flow goes back to the gateway and follows the *Forest or invariant has changed* flow. Since the invariant has changed by the FI update and whenever the shareholders conduct a voting, the next activity is to check if the invariant is still valid. That activity takes the invariant and ensures that the current forest values satisfy the FI. While satisfying, the flow goes back to the Invariant satisfied event. Otherwise, there are any deviation from the wished forest state and the FI condition is violated. Consequently, the system automatically triggers compensating activities leading to forest state changes again (the *Time has passed* event indicates that time is needed and should elapse after activities have

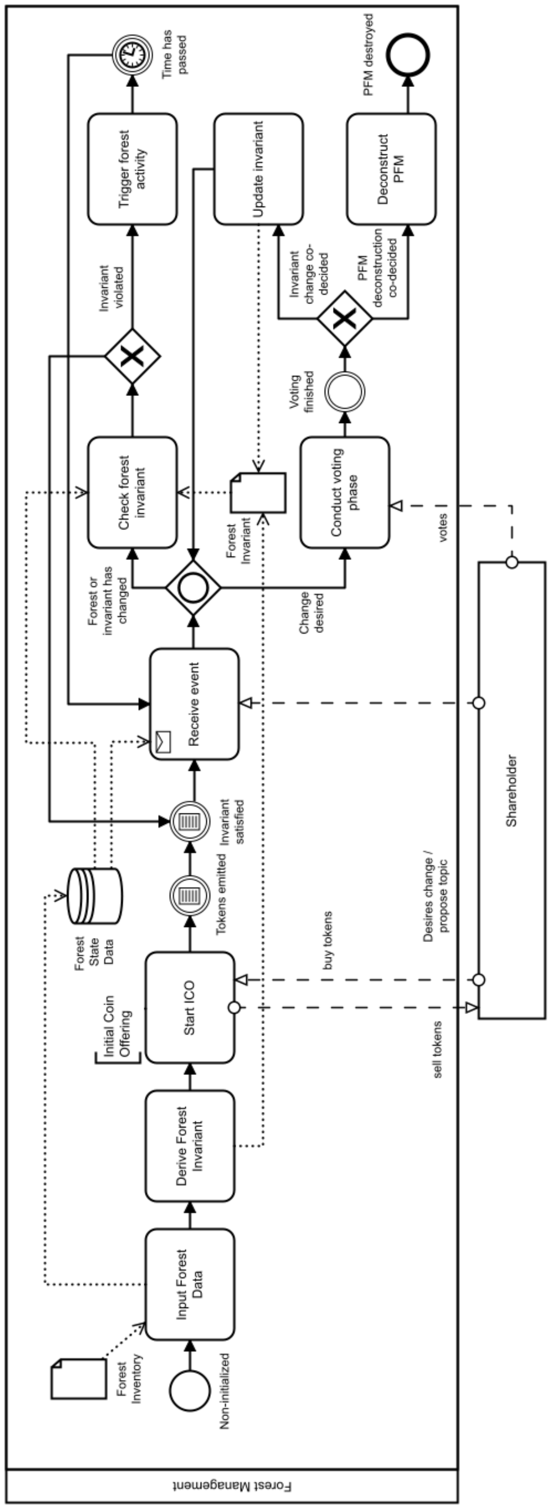

FIGURE 6.2: Life cycle process of a forest governance system for participatory decision-making based on DLT

been triggered). This is a loop starting from *Receive event* to the *Time has passed*. The exit condition is met whenever the forest state satisfies the FI.

After a voting for deconstruction has finished, the branch PDMS deconstruction co-decided will be taken, that means the shareholders have to co-decide against the further existence of the PDMS. At this point, the outcome is the *deconstruction phase (3)* via the activity *Deconstruct PDMS* and ends with the event PDMS destroyed.

Remarks to the Life Cycle Process

Beyond the life cycle process discussed beforehand, there are further explanations worth considering to provide a comprehensive understanding.

Data Insertion. The immediate action is to insert the data of the FI into the DLT database, more precisely the FSDB. Attention should be paid to this point, as both storage capacity and authenticity of data being inserted are critical. First, large amounts of data may usually be stored in distributed cloud file storages instead of multiplying them across all DLT nodes (Wilkinson, Lowry, and Boshevski, 2014). This way, data aggregations can be used to reduce the amount of data. Second, ensuring data correctness is challenging. While DLT let contracts and data become solid and tamper-proof, that the data are correct and represent the reality can not be guaranteed. To tackle this problem in the forest domain, it might be mentionable that the forest is publicly visitable and everyone is able to verify the data. Lastly, in a PDMS, we could also argue that the data insertion process might work in a participatory manner.

Token / Shares. Tokens are part of the incentive schema on DLT (Catalini and Gans, 2016). Typically, tokens are shares held by shareholders where every stakeholder might become a shareholder. A decentralized organization such as a PDMS has assigned a token that, in turn, has a demand-driven course. That way, every shareholder has an interest to behave according to the interests of stake- and shareholders since they all affect supply & demand.

Voice to co-decide. Voting systems are established to coordinate among participating members (Osgood, 2016). The voice gives someone the right to co-decide or to propose topics. Every stakeholder has that right as he or she has become a shareholder by buying tokens. An example for a co-decision might be the voting question whether the amount of timber for energy purposes should be increased (to apply the example mentioned above). In this regard, the existence of a multi-stage voting system could be discussed where veto power is given. A forester or an environmentalist might have veto power to pursue legal purposes or higher interests.

6.4 Economic Implications and Business Model

We believe that our PDMS vision will both target inequalities among affected stakeholders and offer new business opportunities to create economic values. Here, we discuss a business model innovation disrupting established forest business models by utilization of DLT benefits. The main disrupting fields can be described alongside the Business Model Canvas (BMC) (Osterwalder and Pigneur, 2013) where we have innovations especially in the sectors of Value Propositions, Customer Relationships/Segments and Revenue Streams. The newly items of the value proposition are the transparent state and activities concerning forest as well as the participation process itself. Moreover, the opportunity to generate additional income through new revenue streams by novel services offered in the context of forest is limited to the wealth of ideas of the shareholders; a completely new set of services based in the forest is imaginable. These services in turn generate new income opportunities. For example, the monetarization of ecosystem services is expected in the future. Ecosystem services describe ecosystems that influence human well-being. The underlying economic value was estimated by the EU at 200 to 300 billion euros. This high economic value is hardly used (Knoke, 2017). The decentralized participation of new stakeholders could make use of these ecosystem services and create additional income streams, especially for forestry enterprises.

In order to make these innovations possible, it is necessary to set incentives for forest owners so they have an interest and increased willingness in handing over the freedom to decide to others. The benefits for a forest owner are, on the one hand, the increased liquidity after (s)he has sold shares (of a well-managed forest) and, on the other hand, the accruing income by margins of additional services. Another factor is the relief provided by a PDMS, i.e., since participation steers the forest management, the forest is managed without active further intervention by the forest owner. This is in line with the above introduced fact that small forests are often not well managed because small forest owner's main jobs are possibly apart from the domain of forest and its management (UNIQUE forestry and land use GmbH, 2018). From shareholder's point of view, the incentive to buy shares is justified by getting co-decision voice to be able to co-decide. Moreover, there is an economic incentive to act in common interests and on favor of the forest since the attractiveness of forest shares is reflected in the price of tokens. Share-based returns on services could also be expected from economic effective forest management.

Beyond the possibilities of an innovative business model, the legal aspects of DAOs and the Smart Contracts on which they are based must be taken into account. Since a permissonless DLT knows no borders, it must be secured by law internationally. Contract law varies widely from country to country, so it is difficult to make a general statement about the legal enforceability of smart contracts. In order to create a framework that, like the current legal system, regulates conventional contracts, the following points must be clarified: contractual capacity, loss of contract due to errors, identification of an offer and acceptance, follow-on contractual relationship, security of conditions and interpretation of the contents of judges and lawyers (Osgood, 2016).

6.5 Conclusion

With this chapter, the foundations for further research was created. Further research can build upon these thoughts made by this contribution. Generally, we have proposed a PDMS by applying benefits of the DLT. To use DLT for governance purposes is not new (Reijers, O'Brolcháin, and Haynes, 2016), but it seems still not be examined intensively so far, especially with focus on participatory decision-making in the field of common goods / forestry. Hence, we have sketched a visionary PDMS aiming at a reduction of inequalities between stakeholders, to set economic incentives for the benefit of the common good / forest owner to reach a better outcome for all by incorporating claims of different stakeholders. Limitations of this system are numerous, i.e., from the specific design of the mentioned life cycle activities (the contribution can more be understood as a general framework instead of specific implementations), the legal aspects, the complexity, acceptance, usability of the system, the specific role of tokens in the so-called token economy, and so forth. Potentials, on the other hand, are possible in ecological, economical, and social areas by inherent DLT features, for example transparency, immutability, openness, and automation of technical processes. DLT can reduce information asymmetries among participants and help to overcome trust issues and, thus, can help to increase acceptance of decision-making methods and decisions itself. Following this, further research might focus on the feasibility of those potentials and the question of how to treat the mentioned limitations, e.g., to address the power structure for decision-makers: distribution constraints of tokens to shareholders, number of shares per shareholders to prevent too much control per stakeholder. Overall, DLT is a promising candidate to disrupt business models (Hwang et al., 2017; Oh and Shong, 2017) in the field of participatory decision-making, that is to change the way people take part in co-decision processes (Lafarre and Van der Elst, 2018), and – in our opinion – to allow participation in the forest management for the better future for all.

Chapter 7

Participation with Distributed Ledger Technology: What Technology to Use?

> Let me tell you, if you're ever making a decision and the principle reason you'll do it is because of money, then it is absolutely the incorrect decision.
>
> Hill Harper

The previous chapter discusses a Participatory Decision-Making System (PDMS) along the use case of common goods (Willrich, Melcher, and Weinhardt, 2019). Within the presented PDMS, the approach of a Distributed Ledger Technology (DLT) is used, to enhance different aspects of participation for common goods. Over time, there emerged a variety of different DLTs, which diverge in several aspects, and which can be described by several crucial decision criteria. The huge increase of DLT alternatives makes it difficult to Decision Makers (DM) to decide for one specific DLT, considering a given use case. As the problem can be approached by taxonomies (Notheisen et al., 2019), which structure the problems and give overviews, they lack in recommending an specific alternative according to a specific use case. Moreover, DLTs are complex technologies, which are not completely understood by researchers and practitioners so far (Berg, Davidson, and Potts, 2019). Hence, this research follows the objective to increase the decision certainty of Decision Makers (DMs), but also to shed light into the research field on how to evaluate different DLTs against the enormously increasing number of different (potential) use cases.

Research Question 3: *Which Distributed Ledger Technology (DLT) has the highest utility for that use case for a Participatory Decision-Making System (PDMS)?*

This work uses – from the discipline Multi-Criteria Decision Analysis (MCDA) – the Analytic Hierarchy Process (AHP) with a reduced design (Koczkodaj and Szybowski, 2015a) of Pairwise Comparison (PC). By default, AHP uses the full design of PC for part judgements. Key contributions of this work are to show this AHP approach with a reduced PC design as a proven methodology to solve the DLT selection problem, to provide a general framework for DMs to decide for a best suited DLT (irrespective of a specific use case), and to decide a DLT alternative for the use case PDMS.

7.1 Introduction

Digitalization reaches almost any realm and evolves many new technologies such as the DLT (Yli-Huumo et al., 2016). On the one hand, DLTs are complex technologies and can be described by multiple criteria. They are not completely understood by researchers and practitioners so far, leading to a broad research field around these technologies (Yli-Huumo et al., 2016). On the other hand, DLT is discussed with many use cases. The growing number of DLTs and the growing number of potential use cases make it a challenge for DMs to decide (with certainty) for one specific DLT. As usual for emerging and innovative technologies, standards and interfaces diverge and need to be homogenized over time, leading to increased switching barriers in the first generations of these technologies. These switching barriers might even never be completely dissolved. Consequently, a vendor lock-in might lead to path dependencies. Therefore, evaluating innovative technologies thoroughly is recommended – especially when these innovative technologies such as DLT could affect the whole business model (Morkunas, Paschen, and Boon, 2019).

This work shows how the AHP, positioned in the field of MCDA, can be used with a reduced design of PC (Koczkodaj and Szybowski, 2015a) to evaluate systematically a discrete set of different DLTs for a specific use case. This approach requires only a reduced number of pairs $o - 1$ (o is the number of criteria) instead of $\frac{(o-1)\times o}{2}$, as typical in the classic full design. In general, the process follows the usual instructions of Saaty (2002) and is consistent to the general process of a MCDA as depicted in Figure 7.1. According to Figure 7.1, the process starts with the identification of DLTs and the identification of crucial decision criteria. The decision criteria are used to evaluate the identified DLT alternatives and are weighted depending on their meaning for the use case, the DLT alternative should be an answer for.

Moreover, this work creates a general MCDA decision framework based on AHP for identifying a DLT with highest utility for a given use case. In difference to other works, a reduced design of PC is used and a Monte Carlo method is applied to give an overview about the probability to recommend a DLT. This gives both academics and researchers insights to the application breadth of the DLTs and might reduce decision uncertainty. Such a framework empowers Decision Makers (DMs) to identify

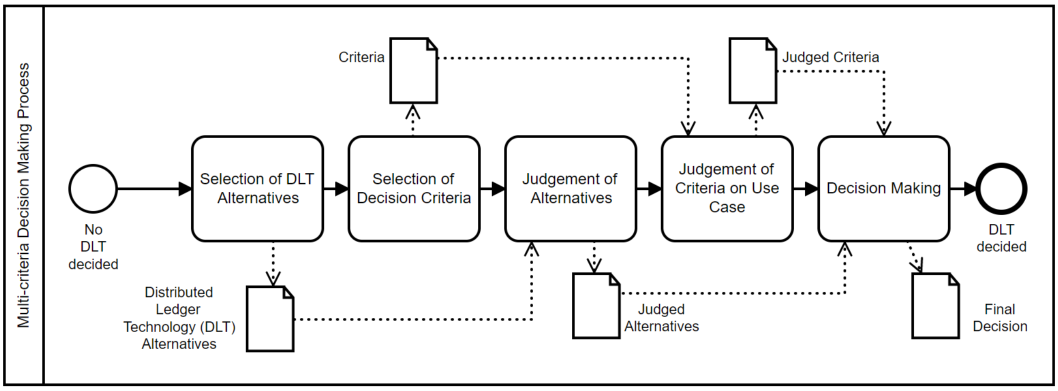

FIGURE 7.1: Decision-making process

a DLT with highest utility without the need of expertise on DLT. DMs only need to specify their preferences in order to apply the resulting decision model on their own use case. At the end, the framework is applied specifically for the PDMS use case. To decrease decision uncertainty and to give a feel for the recommendation, this work finishes with a sensitivity analysis for the recommended DLT alternative for the use case PDMS and illustrates how recommendations can further be analyzed.

In general, a MCDA is used to tackle the DLT selection problem. Within the field of MCDA, a variety of methodologies exists, each of them with individual disadvantages or advantages, examined and applied in different domains so far (Velasquez and Hester, 2013a). MCDA deals with multi-criteria decision problems where multiple criteria behave mutually dependent and/or conflicting. Because of its general popularity (Kaya, Colak, and Terzi, 2019), its ease of use, and its broad applications in various domains (Vaidya and Kumar, 2006a), the AHP is used (Saaty, 2002) to conduct the MCDA. AHP does not presuppose specific values at a numeric scale for each criteria and for each alternative. Instead, Pairwise Comparison (PC) is used to judge on the importance of each criteria to each alternative. These judgements are operationalized to a numeric scale and treated as criterion manifestations for the given alternatives. This approach allows to deal with vague alternatives descriptions where such specific criterion manifestations are not (completely) given. Nevertheless, PC prone to inconsistencies between pair judgements and the pairs increase very fast to new criteria. For this reason, this work proves a reduced design of PC, which was proposed by Koczkodaj and Szybowski (2015a). This is – to the best of the author's knowledge – the first combination of AHP with this reduced PC design.

7.2 Analyzing Distributed Ledger Technology Alternatives

The rise of DLT has most probably begun when Satoshi Nakamoto (a person or a group of persons) had published his understanding of the blockchain technology in

2008 (Nakamoto, 2008). Blockchain can be understood as one potential implementation of a DLT (Cachin, 2016). The potentials of a DLT come from its distributed structure – resulting in the missing necessity of an intermediary or a central unit. Where distrust to intermediaries or concentrated power can become a problem, DLTs provide an alternative way to interact (Hawlitschek, Notheisen, and Teubner, 2018). Intermediaries like lawyers, brokers, or bankers might no longer be a vital or indispensable part of transactions. Through its shared and transparent database and its consensus mechanisms, DLTs enable transactions between decentralized parties in a verifiable and permanent way. The transactions are persistent in a transparent, immutable, and traceable way (Nakamoto, 2008) and consequently protected from deletion, tampering, and revision (Iansiti and Lakhani, 2017). Furthermore, DLTs may have the ability to trigger transactions automatically. With that feature, referred to as smart contracts, DLTs are empowered to execute programs at specific (time) events (Buterin and Others, 2014). Beyond widely discussed cryptocurrencies, voting systems (Osgood, 2016), or digital organizations (Jentzsch, 2016a) are nowadays discussed applications for DLT, partly discussed under cryptoeconomics or token economy. Additionally, DLT-based governance is gaining popularity (Beck et al., 2016; Böhme et al., 2015).

7.2.1 The Distributed Ledger Technology Alternatives

Richard, Mamel, and Vogel (2019) have elaborated the DLT alternatives Cardano, DFINITY, EWC, EOS, Ethereum, Hedera Hashgraph, Hyperledger Fabric (HLF), IOTA, Kadena, Neo, Nervos, Tendermint, and Tezo. This enumeration covers also the most used DLTs within the energy sector, where 50 % use Ethereum, 11 % HLF, 10 % EWC, 7 % Tendermint, and 2 % others (Andoni et al., 2019). Further, because some DLT alternatives do not satisfy some fundamental requirements, some exclusion criteria (EC) are defined. For each exclusion, the justification for this decision is given.

A minimal level of interoperability between different DLTs (EC1) must be given. For example, this is important if several use cases are interconnected among themselves and have different requirements, and therefore different DLT are used. At the same time, it is difficult for a company to determine which DLT will prevail on the market (above mentioned vendor lock-in and switching barriers). Interoperability between DLTs ensures that data can be exchanged between different use cases. DIFINITY, EOS, NEO and Nervos, IO-TA and Tezos do not have sufficient interoperability with other DLTs. Further, when using a DLT, it is recommended that the technology is developed open source (EC2) in order to enable (a sufficient number of) developers to deal with the code (to develop it further), to increase acceptance and trust for the DLT itself, to find errors, or to achieve transparency (transparency helps to enhance data security and user anonymity (Richard, Mamel, and Vogel, 2019)) – to mention some. These EC eliminates IOTA and Hedera Hashgraph as alternatives. Many applications require the use of smart contracts, which, however, are supported by the remaining DLTs. If interoperability (EC1), open source development (EC2), and support for smart contracts are presupposed for the DLTs, Cardano, EWC, Ethereum, HLF, Kadena and Tendermint remain.

- Cardano [CA] is a public DLT, which was developed mainly by scientific research institutions. As consensus mechanism, the PoS protocol is used. Via the Daedalus Wallet, users can easily access the DLT, and developers can develop smart contracts and Dapps via the programming language Plutus (Cardano Foundation, 2019).
- Ethereum [ET] puts special emphasis on the rapid development of applications, security and efficiency. A DLT with an integrated Turing complete programming language Solidity is provided for this purpose (Andoni et al., 2019). Ethereum is based on a PoW consensus mechanism which will be replaced by a PoS protocol in the future. Ethereum is a public and permission-free DLT (Richard, Mamel, and Vogel, 2019).
- EWC [EW] is a public DLT platform developed especially for the energy industry. While the DLT is public, the validation of transactions is restricted. As in Ethereum, smart contracts can be programmed via Solidity, but other programming languages can also be used. Particular attention is also paid to scalability, low transaction costs and low energy consumption through the PoA consensus mechanism (Energy Web Foundation, 2019).
- HLF [HL] stands for Hyperledger Fabric and was designed by the Linux Foundation and offers a modular system for the use of access-restricted (private) DLTs. Due to the modular structure, the consensus protocol can be exchanged, which allows a high degree of adaptability. Smart contracts can also be written in common programming languages such as JavaScript, which simplifies the development of new smart contracts (Androulaki et al., 2018).
- Kadena [KA] is a public DLT that allows programming smart contracts using the programming language Pact. This should a secure, fast and consistent DLT technology (Martino and Popejoy, 2019).
- Tendermint [TE] is a DLT based on Byzantine fault tolerance, which is ensured by the consensus mechanism Tendermint Core. Tendermint Core is responsible for ensuring that transactions are synchronized identically on all devices, while an additional application interface allows transactions to be processed in any programming language. Tendermint is designed to be easy to use and understand while delivering high performance (Tendermint Foundation, 2017).

Abbreviation	*Name of Criterion*
IS	IT security
EE	Energy efficiency
PL	Programming languages
LA	Level of maturity
SA	Scalability
MO	Modularity
LD	Level of decentralization
TC	Transaction costs
FT	Finality of transaction

TABLE 7.1: Collection of decision criteria

7.2.2 Selection of Decision Criteria

The decision criteria are found in such a way to differentiate between the alternatives best possible. The criteria selection process is based on established literature in the field of DLT. The criteria set contains extracted decision criteria defined by Richard, Mamel, and Vogel (2019) and defined by Kannengießer et al. (2019). On the basis of Kannengießer et al. (2019) and Richard, Mamel, and Vogel (2019), 37 decision criteria are identified in total. Decision criteria that do not allow to distinguish sufficiently between DLT alternatives are excluded. Decision criteria with high resemblance or synonyms are compared and combined together. For instance, the criterion "non-repudiation" mentioned by Kannengießer et al. (2019) must be guaranteed by every DLT, and the criterion "availability and stability" listed by Richard, Mamel, and Vogel (2019) show no significant differences between the alternatives and are therefore not considered as criterion. Kannengießer et al. (2019) additionally name "maintainability" as a criterion, but there are no significant differences between the alternatives as they are all open-source developed by a foundation (Richard, Mamel, and Vogel, 2019). The final decision criteria set is given in Table 7.1. The abbreviations of Table 7.1 are also used in the remainder of this section.

In the following, the decision criteria are explained in more detail. IT security (IS) considers the used protocol, the asymmetric encryption, the cryptography by hashing and different attack scenarios. This criterion is a combination of "vulnerability resistance", "level of trust towards nodes", "level of encryption", "integrity", "confidentiality", that are mentioned in Kannengießer et al. (2019). The level of decentralization (LD) means the number of independent nodes involved in the validation and consensus finding process of the DLT. Level of maturity (LA) of a DLT is mentioned by Richard, Mamel, and Vogel (2019), because a low level of maturity leads to higher probability for unfound errors and is a risk for DMs. Finality of a transaction (FT) is elicited as a very important criterion for company's trust. If transactions can be changed after a fork, this is a major impairment of the critical infrastructure. Kannengießer et al. (2019) names the criterion "likelihood of forks". Richard, Mamel, and Vogel (2019) list scalability (SA) as a criterion to measure how many users can use the DLT and how many transactions can be made per second. For instance, this is important for the application of IoT, as many small devices and sensors could be integrated (Richard, Mamel, and Vogel, 2019). Kannengießer et al. (2019) classify performance into the eight criteria: "block creation interval", "block size", "energy efficiency", "propagation delay", "required bandwidth", "scalability", "throughput", and "transaction validation speed". The criterion scalability of Richard, Mamel, and Vogel (2019) also includes "throughput", "validation speed". Therefore, only scalability (SA) is considered. Furthermore, Kannengießer et al. (2019) mention "block size", "propagation delay", "required bandwidth", and "block creation interval" as criteria. These are not considered because they are interdependent already contained by IT security (IS). Another criterion mentioned by Kannengießer et al. (2019) and Richard, Mamel, and Vogel (2019) is energy efficiency (EE), which measures the energy input in relation to the output (transactions). Richard, Mamel, and Vogel (2019) also list the criterion transaction cost (TC). The developer usability is primarily responsible for the medium- and long-term success of the DLT as it measures how easily the DLT can be improved. For the development of smart contracts, the criterion programming languages (PL) is selected (is there the possibility to use standard programming languages or have developers new programming languages to be learned). Kannengießer et al. (2019) also list the criterion modularity (MO) to measure how simple different modules of the DLT, such as the protocol, can be exchanged.

7.2.3 Judgement of Decision Criteria for the Alternatives

According to the AHP (Saaty, 2002) and Chapter II, the judgements were conducted by means of Pairwise Comparison (PC) using a reduced design (Koczkodaj and Szybowski, 2015a). For each decision criterion of these pairs, it is decided how intensive it is fulfilled by the alternative in comparison to another, i.e. PC follows the question whether one alternative fulfills a decision criterion more than another. To decide for one specific alternative, Saaty's scale (see Table 3.1) are used for the judgements. There are nine decision criteria IS, EE, PL, LA, SA, MO, LD, TC, and FT given and each of them needs to be evaluated separately with respect to the alternatives CA, EW, ET, HL, KA, and TE. For each of the resulting nine decision matrices, a carefully and precisely conducted PC with an reduced design were applied. The results of these pairwise judgements and the aggregation of the resulting decision matrices are presented in Table 7.2. A PC matrix is calculated as described by Equation 3.4 for each criterion, i.e. nine square and reciprocal PC matrices and priority vectors result. Since the reduced design of PC is used, there is no need to check for inconsistencies by deriving a Consistency Ratio (CR) (Saaty, 1977). By using the reduced design of PC, each PC matrix is assumed to be consistent, because the reduced number of pairs make no contradictions possible.

	IS	EE	PL	LA	SA	MO	LD	TC	FT
CA	.1300	.0933	.0815	.0362	.0556	.1000	.1000	.0698	.1922
EW	.1300	.5367	.0815	.0772	.2778	.1000	.1000	.3184	.1922
ET	.3170	.0393	.2238	.2834	.0556	.1000	.5000	.0776	.1007
HL	.0530	.1980	.4500	.2834	.2778	.5000	.1000	.4568	.1922
KA	.3170	.0393	.0815	.0362	.0556	.1000	.1000	.0387	.1304
TE	.0530	.0933	.0815	.2834	.2778	.1000	.1000	.0387	.1922

TABLE 7.2: Priority matrix

These nine decision matrices, being synthesized to priority vectors for each criterion, are finally integrated in Table 7.2. The matrix in Table 7.2 can be read in such a way that, for instance, DLT alternative CA, that is Cardano, fulfills criterion IS, that is IT security, with 13 % and EE, that is energy efficiency, with 9.33 %.

7.2.4 Analysis of the Criterion-based Alternative Judgement

To increase the decision certainty of DMs, a further impression is given by Figure 7.2. It shows the relative distribution of each alternative with respect to each rank. The distribution was created by a Monte Carlo simulation (Fryer and Rubinstein, 1983). For this purpose, so-called preference profiles were used, meaning a specific combination of weights of criteria. While an arbitrary preference profile is contained by $\mathbb{R}^9$ (nine criteria), the simulation approximated with 5^9 preference profiles, i.e., each criterion was assigned a value of the set $1, 2, 3, 4, 5$ on a rotating basis. The resulting vector was normalized to reach a valid priority vector. This preference profiles given, a randomized and uniformly distributed sample of 5.000 are used to calculate for each of them the most preferred alternative. After this, occurrences of the alternatives are counted with their corresponding ranks and a relative distribution were derived.

As shown, a high relative distribution for rank 1 with around 85 % is assigned to the alternative HLF. Relative distributions of around 62 % was assigned to EWC and 36 % to Etherium for rank 2. For rank 3, 59 % are distriuted to Ethereium and 37 % to EWC. Rank 4 is mainly dominated by Tendermint with around 90 % and rank 5 and 6 are filled with Cardano and Kadena. These relative distributions are important for the DM if, for example, HLF is no candidate to be implemented due to political reasons or technical barriers. In these cases, it is worth to take alternatives into account with higher ranks. DMs are sometimes faced with fuzziness, resulting in a priority vector with a certain degree of fuzziness and therefore uncertainty. Whenever the DM gets an alternative with a low relative distribution, low changes on the criterion priorities might lead to another alternative. Errors might lead to a wrong DLT adoption with possibly adverse consequences. Beyond this, the relative distributions give a general insight into the application breadth of these alternatives. That way, HLF

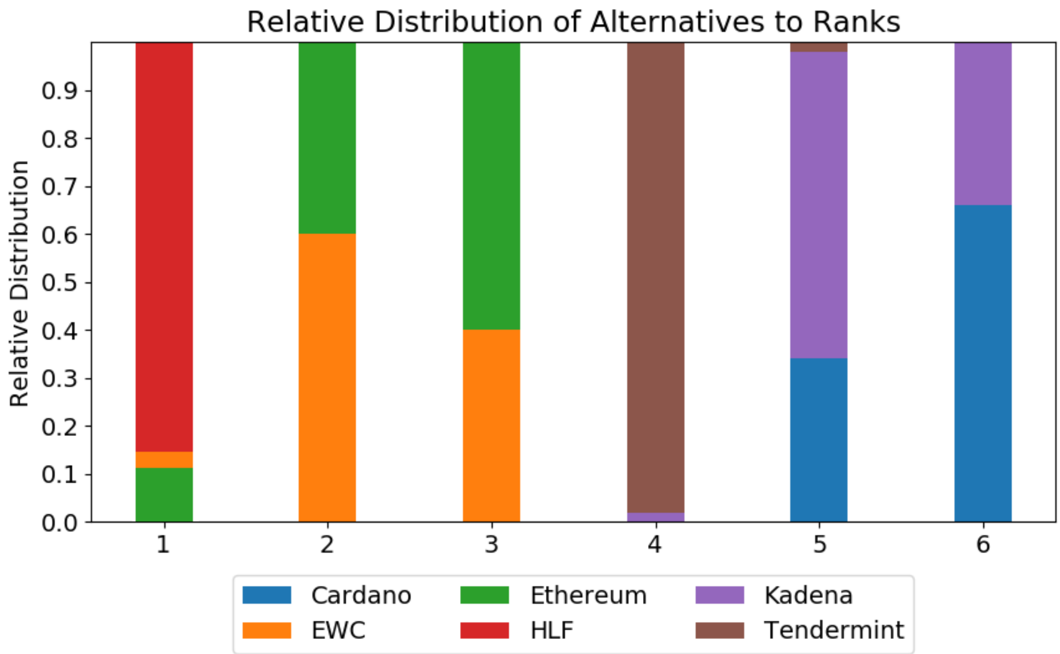

FIGURE 7.2: Relative distribution of alternatives to ranks

seems to be an alternative having broad application potentials for many different preference profiles.

7.3 The Case of the Participatory Decision-Making System

In this section, the judgement for the case of a Participatory Decision-Making System (PDMS) (Willrich, Melcher, and Weinhardt, 2019) is documented. By means of the given decision criteria, the alternatives, and the judgements between these, the evaluation of the use case can be processed. Further information to the use case PDMS can be found in Chapter 6. In the following, the development of the final relative weights for each criterion is described, a final decision is derived, and the robustness of the decision is evaluated by a sensitivity analysis. The pairwise judgments explain on a detailed level which criterion is how far more important than another. This process explains understandable the final weight development and makes the criteria judgements transparent. This judgements are directly related to the requirements of the use case PDMS.

7.3.1 Prioritization of the Criteria

Table 7.3 shows the reduced set of pairs used for the comparisons. The selection of the pairs to be judged are created in a randomized way to avoid biases caused by the explicit selection of criteria pairs. As designed by Koczkodaj and Szybowski (2015a), each criterion is required to be present at least once considering all criteria contained by the identified pairs.

Criterion		Weight	
left	right	left	right
Programming language (PL)	Level of maturity (LA)	1	5
Level of decentralization (LD)	Finality of transaction (FT)	5	1
IT security (IS)	Programming language (PL)	7	1
Level of decentralization (LD)	Transaction costs (TC)	5	1
Modularity (MO)	Transaction costs (TC)	1	5
IT Security (IS)	Energy efficiency (EE)	5	1
Scalability (SA)	Modularity (MO)	5	1
Level of maturity (LA)	Modularity (MO)	5	1

TABLE 7.3: Pairwise comparisons for the Participatory Decision-Making System

The values of Table 7.3 are the judgements according to the scale of Saaty (2002), also shown in Table 3.1. For example, the criterion programming language (PL) in comparison to level of maturity (LA) is $\frac{1}{5}$ and vice versa, i.e., the latter one is 5 times ("Strong importance" according to Table 3.1) more important than the former one. The values are created on the basis of the question whether programming language (PL) or level of maturity (LA) is more important for the use case. The weights of Table 7.3 are created in a carefully and thoroughly manner and are strongly connected to the use case PDMS (Willrich, Melcher, and Weinhardt, 2019), that is described in Chapter 6.

$$X = \begin{array}{c} \\ IS \\ EE \\ PL \\ LA \\ SA \\ MO \\ LD \\ TC \\ FT \end{array} \begin{array}{c} \begin{array}{ccccccccc} IS & EE & PL & LA & SA & MO & LD & TC & FT \end{array} \\ \begin{pmatrix} 1.00 & 5.00 & 7.00 & 1.40 & 1.40 & 7.00 & 0.28 & 1.40 & 1.40 \\ 0.20 & 1.00 & 1.40 & 0.28 & 0.28 & 1.40 & 0.06 & 0.28 & 0.28 \\ 0.14 & 0.71 & 1.00 & 0.20 & 0.20 & 1.00 & 0.04 & 0.20 & 0.20 \\ 0.71 & 3.57 & 5.00 & 1.00 & 1.00 & 5.00 & 0.20 & 1.00 & 1.00 \\ 0.71 & 3.57 & 5.00 & 1.00 & 1.00 & 5.00 & 0.20 & 1.00 & 1.00 \\ 0.14 & 0.71 & 1.00 & 0.20 & 0.20 & 1.00 & 0.04 & 0.20 & 0.20 \\ 3.57 & 17.86 & 25.00 & 5.00 & 5.00 & 25.00 & 1.00 & 5.00 & 5.00 \\ 0.71 & 3.57 & 5.00 & 1.00 & 1.00 & 5.00 & 0.20 & 1.00 & 1.00 \\ 0.71 & 3.57 & 5.00 & 1.00 & 1.00 & 5.00 & 0.20 & 1.00 & 1.00 \end{pmatrix} \end{array} \quad (7.1)$$

The matrix 7.1 shows the PC matrix for the decision criteria judgements against the use case. It is important to note that only the values shown in Table 7.3 are used to elicit the initial weights and the others are derived automatically by the systematic completion approach of Koczkodaj and Szybowski (2015a). As usual, the diagonal is filled with 1, since each criterion is neither more nor less important than itself. The approach does not allow inconsistencies, thus no Consistency Ratio (CR) is required (CR shows the normalized ratio of consistency of a PC matrix). The values of matrix 7.1 can be read as follows: EE is 5.0 times more important than IS. Due to the reciprocity condition, IS is 0.20 times less important than EE.

Criterion	IS	EE	PL	LA	SA	MO	LD	TC	FT
Priority	0.119	0.024	0.017	0.085	0.085	0.017	0.426	0.085	0.142

TABLE 7.4: Priorities for the use case Participatory Decision-Making System

Once the complete PC matrix is achieved, the classic procedure of Saaty (2002) finishes the process and a priority vector results, showing for each criterion the resulting relative weight. The Table 7.4 shows this relative weight for each criterion with respect to the overall utility, that is to decide a DLT that maximizes the utility for the use case PDMS. As displayed in Table 7.4, the aggregated value for level of decentralization (LD) gains the highest weight. The values of Table 7.4 are consistent with and illustrated by the bar chart shown in Figure 7.3.

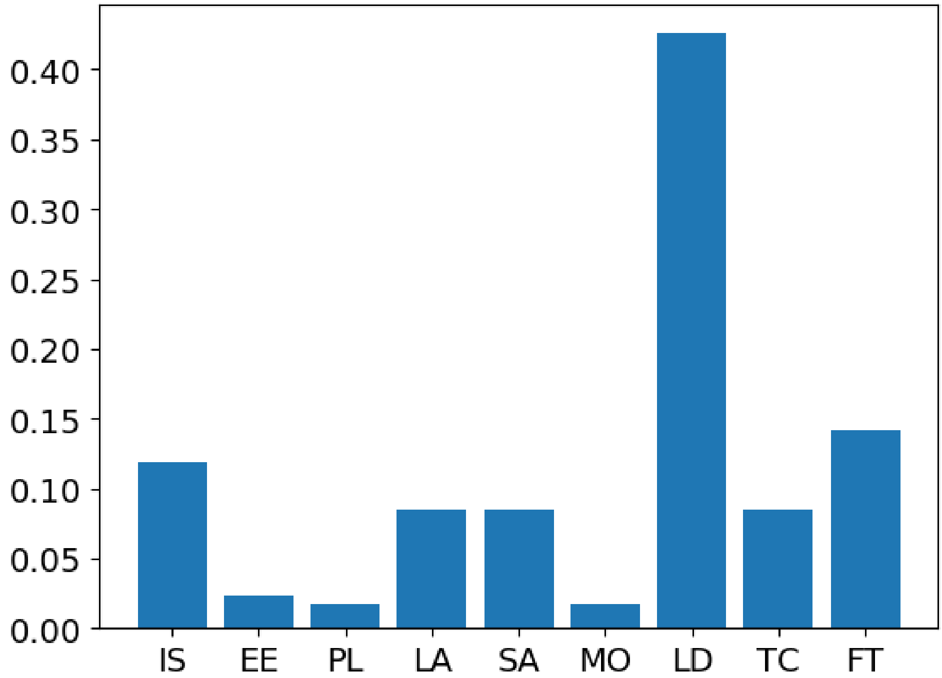

FIGURE 7.3: Priority vector for the Participatory Decision-Making System

7.3.2 Final Decision and Analysis

Once the priorities of each alternative with respect to each decision criterion (Table 7.2) and the priorities for the decision criteria with respect to the utility (Table 7.4) are judged, the final decision is calculated and analyzed. The result of the final decision for the introduced use case is shown in Table 7.5. As shown, Ethereum has reached the highest utility value, followed by HLF, EWC, Tendermint, Kadena, and Cardano.

The resulting utilities of Table 7.5 are depicted in the bar chart of Figure 7.4. These values are equally to those of Table 7.5.

DL	Cardano	EWC	Ethereum	HLF	Kadana	Tendermint
Utility	0.1044	0.1585	0.3068	0.1837	0.1139	0.1325
Rank	6	3	1	2	5	4

TABLE 7.5: Final decision

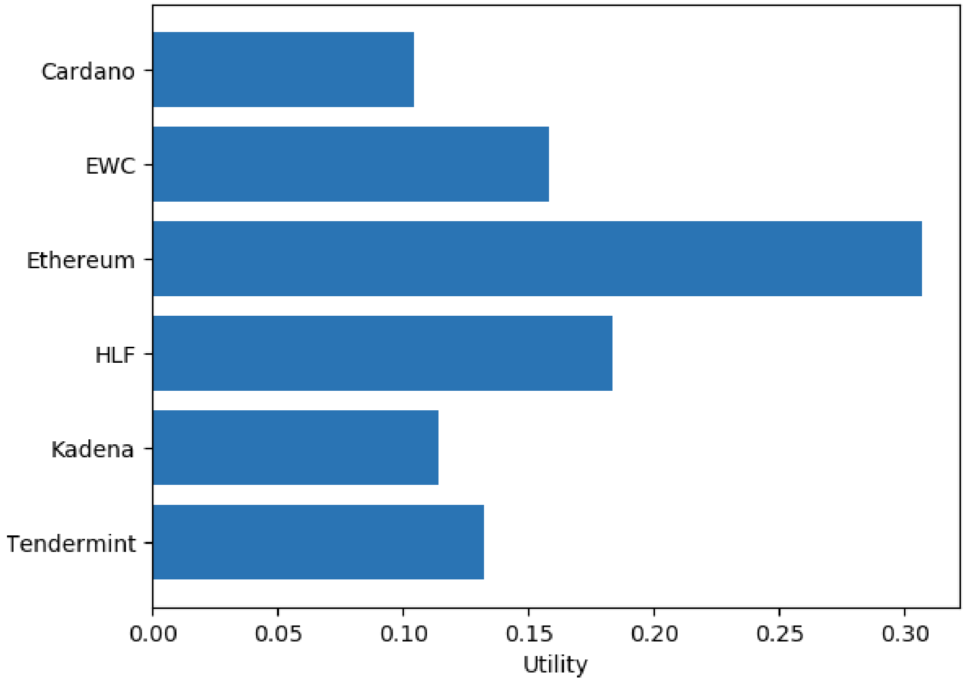

FIGURE 7.4: Final decision for a Distributed Ledger Technology for the case Participatory Decision-Making System

The final decision (see Table 7.5) shows that the first rank is assigned to Ethereum. This can be attributed to the fact that Ethereum has the highest level of decentralization (DL) among all alternatives. Further, this criterion achieves the highest weight in Table 7.4. HLF is placed at rank 2. HLF is particularly suitable for a high degree of modularity, the non-existent transaction costs, and the possibility of programming in Java and JavaScript – both of them are highly established and accepted programming languages. EWC is positioned at rank 3 due to its energy efficiency. Tendermint, Kadena, and Cardano take the last three ranks.

A sensitivity analysis is shown in Figure 7.5. These sub figures show the change in intensity and thus the sensitivity of each criterion with respect to each alternative. To reach this and according to literature (Geldermann and Lerche, 2014), each value of the criteria weights was changed (see Table 7.4 for original values) from 0.1 to 1.0 (borders inclusive) and the vector was normalized again to be consistent. Please note that the blue bar depicts the decided criterion weight of Table 7.4 as reference. For each change in the criterion value, the change in the given utility for each alternative is depicted. The figure extends the analysis and shows that a decrease in IT security can not change the ranks of the given alternatives. But a decrease in energy efficiency might cause a change between 0.2 and 0.4, but the original weight is a bit over 0.0. After a change, EWC is the winner. At programming languages, HLF becomes the winner once the criterion is changed from a bit over 0.0 to around 0.6. Further, level of maturity causes no rank reversal while scalability causes a change at 0.6 in the favor of HLF, EWC, and Tendermint (in this order). Beyond this, changes in modularity appear between near 0.4 and level of decentralization needs a decrease below 0.2 to change to HLF. Finality of transaction as criterion does not change the alternative ranking and the transaction cost changes the preferred alternative once the weight is moved from 0.098 to near 0.4. The most critical weights are therefore modularity, level of decentralization, and energy efficiency.

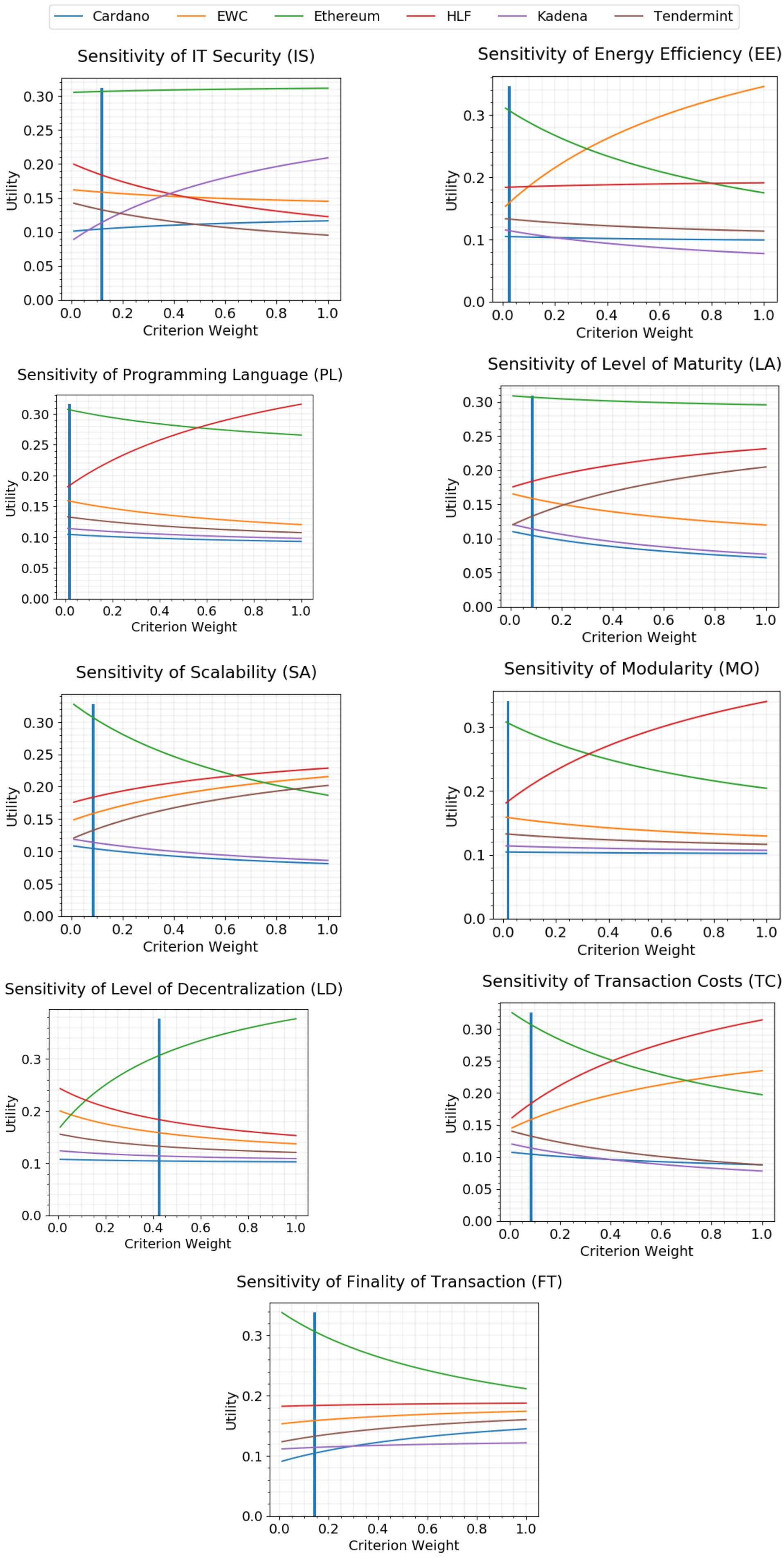

FIGURE 7.5: Results of sensitivity analysis for the case Participatory Decision-Making System

7.4 Conclusion

With this work, AHP – positioned in the field of MCDA – with a reduced design of PC is used. Usually, MCDA is actually most used for complex political and environmental problems, and is here applied to the DLT selection problem. A general framework and a decision model for DLT selection problems are created. The identification of decision criteria and DLT alternatives follows a systematic elicitation approach. One limitation here is that the identification of the decision criteria and alternatives is mainly based on Richard, Mamel, and Vogel (2019) and Kannengießer et al. (2019). The decision criteria were judged thoroughly against the DLT alternatives, which are analyzed by a Monte Carlo simulation – irrespective of any specific use case. This simulation gives an overview about the probability to reach each DLT alternative on the level of different ranks. This makes the decision model more general to other use cases, increases the decision certainty of DMs, and shows the application breadth of the DLT alternatives, respectively.

This work exemplifies its applicability specifically to the PDMS, but is not limited to this. For this purpose, the decision model being filled with DLT alternatives and decision criteria is reused. There is only a specification of the preferences on the level of criteria for the given use case PDMS necessary. Then, Ethereum as DLT is recommended, and the result is analyzed with a sensitivity analysis, to show the robustness of the DLT recommendation. This sensitivity analysis, together with the relative distribution to reach the corresponding DLT alternatives, increases the decision certainty for the recommendation of the DLT alternative to the use case PDMS. That way, the work shows how DMs can adapt the decision model to their own needs in order to apply it to their use case. Put differently, when it comes to adoption, a DM needs to re-evaluate the decision criteria with respect to their specific use case, but the DM does not need to elicit DLT alternatives, DLT decision criteria, or to make an evaluation between those. Instead, they benefit from the Monte Carlo simulation in order to compare their specific DLT recommendation to the probability of the choice for this DLT recommendation. This is one of the practical implication of this work.

With respect to academic implications, this work applies the AHP to the DLT selection problem by means of a reduced design of PC at first. Open questions remain with respect to different MCDA approaches that might also be applicable to the DLT selection problem. Further research also embraces the identification of additional DLT alternatives or additional decision criteria. In the course of time, decision criteria might become more or less important, newly DLT alternatives might arise or existing DLT alternatives might disappear. Therefore, further limitation of the work is that it can just be a snapshot of the today's DLT landscape since DLT developments are still in motion (initial test projects are currently being implemented).

Chapter 8

Achieving Social Welfare Over Common Goods[4] [5]

> Communities don't think, don't believe, don't want, don't have needs, don't have interests and don't make decisions. Only individuals have minds that generate desires and needs - and only individuals can make choices and decisions.
>
> Harry Browne

Participatory decision-making on common goods remains a challenge, especially as long as the good's provision shall satisfy the participants' preferences at best. To combine two of these challenges, this work focuses on methodologies to, first, find the participant's optimal solution, and, second, to give incentives to these participants to announce their optimal solution in a truthful way to the superior preference aggregation process. Both challenges need to be solved to make the outcome (more) efficient at the end.

Research Question 5: *How to incentivize truth-telling in participatory multiple-criteria decision-making over management alternatives of a common good?*

For this purpose, the field of Multi-Criteria Decision Analysis (MCDA) is applied to finding participant's optimal solutions, which is theoretical combined with the well-known public project problem (also known as public good game). To reach a pareto-efficient outcome, the Vickrey-Clarke-Groves (VCG) payments are applied to make it a weakly-dominant strategy for each participant to announce its preferences about alternatives truthfully. At the end, the decision- and game-theoretical model is exemplified by a forestry use case, which is evaluated by a multi-agent simulation.

[4] An earlier version of this chapter has been published as Willrich, Straub, and Weinhardt (2020)
[5] An earlier version of this chapter has been published as Willrich, Straub, and Badewitz (2021)

8.1 Introduction

Blockchain technology, its extensions, and breadth of applications employ the community around IS (information systems) researchers. Apart from applications focusing on FinTech, nowadays research also affects Decentralized Autonomous Organisations (DAO) (Jentzsch, 2016a) or Blockchain-Enabled E-voting (BEV) (Kshetri, 2018). BEV promises to speed up, to simplify, and to reduce costs of elections (Hjalmarsson et al., 2018) and could therefore lead to higher voter turnouts. As outlined, BEV was already used for corporate, community, city, and national voting (Kshetri, 2018).

In general, voting aims at deciding collectively one specific outcome. As voting programs as smart contracts can be designed, implemented, deployed, instantiated, and executed on-chain (on the blockchain), this research focuses on the design of such smart contracts. Especially votings about common goods such as parks, parking areas, or forests need to involve many people to reach the best outcome for all, since common goods (in contrast to public goods, it is also rivalrous since its resources are scarce) provide services for everyone. Due to their characteristics, nobody can be excluded from its usage or consumption (the non-excludability condition). The involvement of users and keeping information transparently promise to increase the acceptance of decisions (Ananda and Herath, 2009), might reduce mistrust (Tanz and Howard, 1991), and require generally binding, reliable, and transparent participation (Reed et al., 2009; Guyot, 2012) – where blockchain can contribute to. The challenge comprises the design of voting contracts in such a way that a desired outcome of the voting initiator is reached, while selfish people with diverging preferences affect collectively a single outcome.

Users have normally diverging preferences over a common good. Voting is used to tradeoff between user's preferences, but it remains a challenge on common goods. The so-called collective action problem occurs exactly when individual rationality does not result in group rationality (Olson, 2009), and the users (in a game-theoretical sense agents) behave strategically – resulting in an inefficient outcome for all. For this reason, smart contracts should consider this incentive structure to serve their purpose. Mechanism design, a sub-discipline of game theory, is already utilized to design consensus mechanisms such as Proof-of-Work (PoW) or Proof-of-Stake (PoS) to reach a consensus among selfish agents, and is here combined on a higher application layer to design the incentive structure for votings.

Since a common good can be provided in multiple ways and it is challenging to differentiate between these options, multi-criteria decision analysis (MCDA) is linked to these mechanism design approach. An efficient outcome needs not only the right incentive structure, but requires also the participants to know their best option. Because – to the best of our knowledge and belief – this intersection was never made, this work extends the public good game to be compatible with an MCDA environment. Agents decide individually using MCDA, derive their willingness to pay for each alternative, an invented social choice function chooses then the alternative with the highest utility for all (maximizing the social welfare), and each agent derives its final utility. To make it a weakly-dominant strategy for everyone to announce true preferences, the Vickrey–Clarke–Groves (VCG) mechanism is used to incentivize truth-telling. Conceptualizing and simulating this theoretical approach is the core contribution of this work.

A common good, equally to public goods, is non-excludable (nobody can be prevented from consumption) and partly rivalrous (someone's consumption subtracts the good and overuse might be an outcome). Due to the rivalry, participants (in a game-theoretical sense *agents*) compete against each other and have diverging preferences over the management alternatives of a common good. Due to its today's importance for - among others - climate change and its highly illustrative power for common goods, this topic is exemplified by means of a forest – in particular, the forest can be understood as a common good (Meurs, 2007). There exists a right to enter German forests, while the forest's ecological services, e.g. biodiversity conversion, recreation, carbon capture, and storage, can be understood as services everybody can consume (non-excludability). This makes the forest a complex system that offers several ecological, economical, and social services (Dieterich, 1953), while the demand for these services varies greatly and depends on preferences of heterogeneous participants (Ananda and Herath, 2003) about its natural and scarce resources (rivalry). Moreover, a discrete set of management alternatives is given, where each alternative is described numerically by multiple criteria. These multiple criteria have different importances from the participant's point of view, resulting in participant-depending (economic) utilities for each alternative - the participants preferences. This proposed model is thus illustrated by a forest management case and an agent-based simulation, tho show how the individual strategic behavior can affect the final outcome.

In the following, participatory decision-making is tackled by means of mechanism design (and public good theory), a sub discipline of game theory. At this, mechanisms are used to incentivize the achievement of a predefined goal. Therefore, mechanism design means to define rules and incentive structures in such a way to reach a desired outcome. When it comes to participatory decision-making for common goods, the participants are faced with the so-called *collective action problem*. This is exactly the case when individual rationality does not result in group rationality (Olson, 2009). Due to the non-exclusiveness condition, participants have incentives to behave strategically (in a game-theoretical sense). Since they are inevitably able to consume the good, they might decide to not contribute to its provision. That is, when participants' preferences are translated to a willingness to pay (the amount they are willing to contribute) and this is coupled to mandatory payments in a monetary unit, the outcome's efficiency could fail due to the free rider problem. When the willingness to pay is decoupled from mandatory payments, they might overestimate their utility, which would an inefficient outcome, too. In such situations, mechanism design can incentivize truthful behavior.

Decision-Making in the Field of Forest Policy

While preferences in the field of forestry diverge and the focus, besides others, is on timber harvesting, recreation, water supply, or biodiversity conversion, it oftentimes results in MCDA. MCDA itself is a powerful methodology to incorporate diverging preferences, to solve such multiple-objective problems and has therefore been proven to be a valuable methodology in the forestry (Kangas and Kangas, 2005) over the last three decades (Ananda and Herath, 2009). Many MCDA approaches were combined with group decision-making (Matsatsinis and Samaras, 2001), which have also been applied in public participation for the forestry (Kangas, 1994). Today's forest decision-making usually follows a top-down principle, i.e., the forest decision power distribution is quite concentrated (e.g. by the forest owner, who can be assumed rational and economically driven (Lönnstedt, 1989)), while other participants remain affected by, but are not involved in forest decision-making. In order to take full effect for the society, thus, forest management must be more aligned to the overall interests.

In particular, a forest offers multiple objectives. It offers renewable resources, conserves biodiversity, acts as a carbon sink, and provides recreational functions in a simultaneous manner. Such a common good needs to and can be managed in different alternative ways, whereas participants have diverging preferences over these alternatives. For example, participants can be classified along the following forest functions (Hanewinkel, 2011). Consumers and the wood processing industry request the productive function. Environmentalists are interested in protecting the nature and maintenance of sustainability and hence address the protective function. Those participants seeking rest in the forest, for instance enjoying the nature and doing sports in the forest (like hikers or mountain-bikers do) request the recreational function. As a result, each management alternative satisfies the participants to a different degree. Therefore, this work describes each alternative by multiple criteria, thus a large number of possible management alternatives is resulting, which are decision problems each participant is able to solve by Multi-Criteria Decision Analysis (MCDA). While doing so, each participant is assumed to be rational and to behave strategically, such that deviating from truth-telling might turn out to be an weakly-dominant strategy. This work demonstrates how truth-telling could be a rational decision in a multiple-criteria decision-making context.

8.2 Related Work

Designing voting mechanisms with mechanism design (as sub discipline of game theory) and even with VCG have already attracted attention from many researchers (Meir, 2018). Among others, research focused on the efficient provision of a public good (Narahari, 2013) or challenges how to decide a public good with strict budget balance (Shao and Zhou, 2016). Beyond this, this research can be embedded horizontally, as it extends the range of applications of VCG mechanisms instead of solving present issues (vertically) VCG mechanisms have. Contributions at the intersection of blockchain, mechanism design, and (e-)voting are rather scarce. Quadratic voting was introduced (Lalley and Weyl, 2018) in the field of voting and is one example for a combination with blockchain (Barrera and Hurder, 2018; Wright Jr, 2019), but most of the contributions are more related to throughput improvements of blockchains or alternative consensus mechanisms for blockchain (Liu et al., 2019).

8.3 The Model

There can four different sources of complexity distinguished across two layers when designing game-theoretical mechanisms (Parkes and Ungar, 2001): (1) the agent layer refers to the complexity agents are faced with while declaring their own type (to get know the own preference) (1.1), i.e. which outcome they prefer and to what extent they have weights and preferences over possibly multiple outcomes. (1.2) refers to the complexity agents are faced with while determining the own strategy in a multi-agent setting, i.e. how to behave to increase the own utility. The second layer (2) is about the infrastructure, where the complexity to determine the result for everyone (2.1) and the complexity to communicate between agents to determine the result belong to (2.2). Following this, this research puts special focus on 1.1, where MCDA is used to help the agents determine the best outcome, and on 1.2 to establish incentives to make it individually rational with a dominant strategy to report truthfully – which is necessary to ensure the allocation to be efficient at the end. The complexities 2.1 and 2.2 are infrastructure-related and are consider the blockchain.

The proposed model contains the mechanism and is completely compatible with a multi-criteria setting, where multiple alternatives are in choice and only one or nothing of them is finally part of an outcome. The model is parameterized by the agent's preferences, which are based on their criteria weights and which are operationalized to their willingness to pay – individually specified for each alternative. An objective decision matrix is presupposed, which quantifies the alternatives. First, the non-monetary utilities over the alternatives are determined using a classic MCDA approach, resulting in utilities for each alternative for each agent. This can also be calculated on the level of part-worth utilities. As shown, it is generally sufficient to state the willingness to pay just once, as the other alternative-specific types can be derived by interpolation based on the non-monetary utilities based on MCDA.

In the end, a social choice function receives all announced types of all agents and returns an – for rational agents – efficient outcome. Since this outcome is achieved by a mechanism being part of the VCG family, the agents end up with a dominant equilibrium, i.e. no knowledge about the others is required to determine one's own optimal strategy among a set of pure strategies for each agent.

8.3.1 The Agents' Non-Monetary Utilities Over Alternatives

To formalize this, m alternatives $A_1, \ldots, A_j, \ldots, A_m \in A$ are defined being contained by the set A to manage a forest. Further, o criteria $C_1, \ldots, C_k \ldots, C_o \in C$ are defined each alternative consists of (as usual in MCDA). It forms together a decision matrix $X = (x_{jk})_{m \times o}$ where each alternative is described numerically by each criterion, see Equation 8.1.

$$X = \begin{array}{c} \\ A_1 \\ \vdots \\ A_j \\ \vdots \\ A_m \end{array} \begin{array}{c} \begin{array}{ccccc} C_1 & \cdots & C_k & \cdots & C_o \end{array} \\ \begin{pmatrix} x_{1,1} & \cdots & x_{1,k} & \cdots & x_{1,o} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ x_{j,1} & \cdots & x_{j,k} & \cdots & x_{j,o} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ x_{m,1} & \cdots & x_{m,k} & \cdots & x_{m,o} \end{pmatrix} \end{array} \tag{8.1}$$

That way, Equation 8.1 shows that a management alternative A_j is listed row-wise while it is described numerically by a criterion C_k column-wise. These alternatives are potential solutions to the problem formulation of how to manage a common good. A value $x_{j,k}$ shows the manifestation of criteria k in alternative k and is subject to $\sum_{A_j \in A} x_{j,k} = 1$ for all $k = 1, \ldots, o$. This common good is further assumed to be held by one private owner p (for provider), who is responsible for applying a specific management alternative A_j or not (no provision means selfish management without involving others in the decision-making). When it comes to provision, different agents $N = \{1, ..., n\}$ are involved in the decision-making. Then each alternative has a different meaning from the agents' point of view, meaning that the preferences diverge over the alternatives.

These meanings are operationalized by non-monetary utilities for these alternatives as shown by Equation 8.2. Since each alternative A_j is described by each criterion C_k, each agent i has those utilities on the level of criteria $\beta^i_{j,k}$ (the part-worth utility). The i's non-monetary utility of an alternative A_j is then given by

$$y^i_j = \sum_{k=1}^{o} \beta^i_{j,k}$$

that is the sum of the part-worth utilities for a specific alternative A_j, with k to denote the consecutive index for the criteria, and with o denoting the total number of criteria. Each non-monetary utility is $y_j^i \geq 0$, since it is assumed that each agent has a minimal part-worth utility greater than zero at least at one criterion (in order to cope with the natural characteristics of a common good).

$$Y^i = \begin{array}{c} \\ A_1 \\ \vdots \\ A_j \\ \vdots \\ A_m \end{array} \begin{array}{c} \begin{array}{ccccc} C_1 & \cdots & C_k & \cdots & C_o \end{array} \\ \begin{pmatrix} \beta_{1,1}^i & \cdots & \beta_{1,k}^i & \cdots & \beta_{1,o}^i \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \beta_{j,1}^i & \cdots & \beta_{j,k}^i & \cdots & \beta_{j,o}^i \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \beta_{m,1}^i & \cdots & \beta_{m,k}^i & \cdots & \beta_{m,o}^i \end{pmatrix} \end{array} \tag{8.2}$$

In order to achieve the part-worth utility $\beta_{j,k}^i$, in MCDA a priority vector is commonly used $w^i = (w_1^i, \ldots, w_k^i, \ldots, w_o^i)$. To reach w^i, an agent i judges the decision criteria such that w_k^i is the quantified importance (the subjective weight) of criterion C_k. After the importances are quantified for each criteria $k = 1, \ldots, o$ to subjective weights, the vector is normalized subject to

$$\sum_{k=1,\ldots,o} w_k^i = 1$$

such that the sum of the weights $w_k^i \in w^i$ is equal to 1.

Then, for instance, agent i perceives criterion C_k as important as w_k^i in relation to others w_l^i with $l \neq k$. At this, a linear utility model is assumed to be given (Steiner and Meißner, 2018b) since $\beta_{j,k}^i$ grows in a linear way to w_j^i. These subjective weights could be achieved by, e.g., pairwise comparisons, point allocations, ranking, or rating. To calculate then i's part-worth utilities $\beta_{j,k}^i$, both the subjective weights w^i and the agent-independent manifestations of the criteria with respect to the alternatives $x_{j,k}$ are incorporated by

$$\beta_{j,k}^i = x_{j,k} * w_k^i \quad \forall\, j = 1, ..., m, \forall\, k = 1, ..., o, \forall\, i = 1, ..., n$$

In this simple linear utility model, the (part-worth) utilities are derived in a strongly linear way. Because utilities usually grow non-linear, these part-worth utilities $\beta_{j,k}^i$ can also be computed in a more sophisticated way (e.g., by the conjoint analysis) to represent the preference of decision-maker more accurately. Then curves like a parabola might be possible. For further information, Steiner and Meißner (2018b) provide a good overview about different utility models such as the ideal point model or the vector model.

Further, the sum over all utilities of alternatives of agent i sum to 1

$$\sum_{A_j \in A} y_j^i = 1$$

and the alternative with highest utility $\max_{A_j \in A} y_j^i$ is mostly preferred, i.e., agent i's choice would then be this alternative.

8.3.2 The Agents' Monetary Utilities Over Alternatives

As identical to the section before, there are multiple alternatives $A = A_1, \ldots, A_m$ given. Apart from the fact that each agent has a non-monetary utility y_j^i for each alternative $A_j \in A$, each agent i has also a monetary utility (the agents' monetary utilities over alternatives), which is calculated by the valuation of agent i for a management alternative (considering the cost for it) and a side payment to or of agent i (further explanations below). The i's valuation is operationalized by the willingness to pay, which is also the type of the agent and denoted with $\theta^i \in \mathbb{R}$ (which can not be negative $\theta^i \geq 0$), and the cost for the alternative to be provided.

It is assumed that information asymmetry is given among the participating agents $i \in N$, resulting in an environment where agents have private information. That way, it is assumed that the type $\theta^i \in \Theta^i$ of agent i is agent i's private value (information), whilst Θ^i is the set of private values of agent i. As the type of agent i is denoted with $\theta^i \in \Theta^i$, a type profile $\theta = (\theta^1, \ldots, \theta^n)$ denotes the types of the n agents involved (θ^{-i} depicts a type profile without agent i $(\theta^1, \ldots, \theta^{i-1}, \theta^{i+1}, \ldots, \theta^n)$ while (θ^i, θ^{-i}) is a shortcut and equal to $(\theta^1, \ldots, \theta^i, \ldots, \theta^n)$). $\Theta = \Theta^1 \times \cdots \times \Theta^n$ is the set of all type profiles.

The i's type (or the willingness to pay) θ^i is associated with the preference vector w^i of agent i. Following this, the willingness to pay for alternative $A_j \in A$ is

$$\theta_j^i = \theta^i(A_j) = \theta^i * \frac{y_j^i}{\max_{A_j \in A} y_j^i}$$

such that the willingness to pay even for non-optimal alternatives is positive. This is attributed to the fact that even non-optimal alternatives have at least minimal value (forest offers, however they are managed, are in everyone's interest).

To align this problem model as realistic as possible, there is also realization cost as contrast to the willingness to pay of each agent i modeled. To provide a management alternative A_j, its cost is allocated among all agents (which is known as the egalitarian principle), such that each agent i is incurred by

$$\pi_j^i = \frac{\pi_j}{n}$$

where π_j are the total realization cost of alternative A_j and n the number agents. The above introduced provider p declares all alternatives' costs and receives that realization cost of the alternative that have been decided by the agents to provide, otherwise the provider p receives nothing. The realization costs are paid by the agents if and only if an alternative is provided.

The mechanism described in the work at hand is on the basis of a particular class that is called *direct mechanisms*, that is of most of studies in focus (Csapó, 2015). Generally, there are $i \in N$ agents in the game, while each has a strategy $s^i(\theta^i)$. Since in direct mechanisms, the strategy is defined as $s^i : \Theta^i \to \Theta^i$, the possible strategies are restricted to the set of possible types, such that the focus lies especially on the *revelation principle* (Myerson, 1981). The direct mechanism is denoted with $\mathrm{D} = ((\Theta^i)_{i \in N}, f(\cdot))$, where $f(\cdot)$ depicts a Social Choice Function (SCF) defined below.

8.3.3 The Social Choice Function and Agent's Monetary Utilities

Afterwards, the agents are asked for reporting their types, such that a decision can be taken. For this purpose, a SCF is responsible for determining an outcome, which is also containing the alternative applicable to the common good. The reported type is denoted with $\widehat{\theta^i} \in \Theta^i$, that might be the agent's true type $\widehat{\theta^i} = \theta^i$, or its untrue type $\widehat{\theta^i} \neq \theta^i$. The following SCF then receives these reported types

$$f : \Theta^1 \times \cdots \times \Theta^n \to O$$

of n agents and assigns each reported type profile an outcome $o \in O$. This SCF solves then the so-called *preference aggregation problem* by processing the reported utilities

$$f(\widehat{\theta}) = (k(\widehat{\theta}), t^1(\widehat{\theta}), \ldots, t^i(\widehat{\theta}), \ldots, t^n(\widehat{\theta}))$$

in order to determine an outcome $(k, t^1, \ldots, t^n) = o \in O$, each consisting of the allocation part k and the payments t^i to or of the agents $i \in N$ (put differently, each outcome o is decomposed into an allocation part $k \in K$ and a payment part $t^i \in \mathbb{R}$ for $i = 1, \ldots, n$). A specific outcome $((k_1, \ldots, k_m), (t^1, \ldots, t^n)) = o \in O$ (shortened denoted with $(k, (t^1, \ldots, t^n)))$ of the alternative choice is afterwards part of the set O, that is

$$O = \{(k, (t^1, \ldots, t^n)) : t^i \in \mathbb{R} \ \forall \ i \in N, \sum_{i \in N} t^i \leq -\Big(\sum_{k_j \in k} k_j \pi_j\Big)\}$$

where all possible outcomes are contained. The mentioned condition in the declaration of set O means that the sum of payments must be lower or equal to the expenses for the cost of the provision of the corresponding alternative if and only if the provision is decided.

With respect to the outcome, $(k_1, \ldots, k_j, \ldots, k_m) = k \in K$ means the allocation that is determined, represented by binary variables declared by the set

$$K = \{K_j : \forall\ A_j \in A, K_j \subseteq \{0,1\}, \sum_{A_j \in A} k_j \leq 1, \forall\, k \in K\}$$

indicating for each alternative $A_j \in A$ whether this alternative is provided $k_j = 1$ or not $k_j = 0$. That way, $k \in K$ means a specific allocation. Given an output $(k, t^1, \ldots, t^n) \in O$, k is an allocation that is calculated by an allocation function $k(\widehat{\theta}) = \{k_j(\widehat{\theta}) : \forall\ A_j \in A\}$ consisting of $k_j(\widehat{\theta}) \in K(\widehat{\theta})$, which is reached by

$$k_j(\widehat{\theta}) = \begin{cases} 1, & \text{if } \sum_{\widehat{\theta}_i \in \widehat{\theta}} \widehat{\theta}^i_j - \pi_j \geq 0 \wedge \sum_{\widehat{\theta}_i \in \widehat{\theta}} \widehat{\theta}^i_j - \pi_j \geq \max_{A_k \in A, A_k \neq A_j} \sum_{\widehat{\theta}_i \in \widehat{\theta}} \widehat{\theta}^i_k - \pi_k \\ 0, & \text{otherwise} \end{cases}$$

while $t^i(\widehat{\theta})$ is calculated by a specific side payment function (see introduced below). When the allocation is calculated without an agent i, then the allocation is depicted as $k^{-i}(\widehat{\theta}^{-i})$, resulting in an allocation that is optimal for a situation where agent i is not present. The function $k_j(\widehat{\theta})$ evaluates to 1 if a given alternative A_j has reached the highest *social welfare*

$$\arg\max_{A_j \in A} \sum_{i \in N} \theta^i_j - \pi_j$$

among the reported types of the agents $i \in N$, meaning there does not exist any alternative that yields higher social welfare.

After an allocation is decided, the utilities of the participating agents $i \in N$ can be derived. A utility $u^i : O \times \Theta^i \to \mathbb{R}$ of agent i can then be calculated with

$$u^i((k, (t^1, \ldots, t^n)), \theta^i) = v^i(k, \theta^i) + t^i$$

where t^i denotes the (side) payment of or to agent i, which is either positive $t^i > 0$ (agent i receives money), negative $t^i \leq 0$ (agent i pays money), or zero. Note that this is also known as a *quasilinear environment*, consisting of an allocation part and a payment part (similar to the superior structure of $o \in O$). The formula

$$v^i(k, \theta^i) = \sum_{k_j \in k} k_j \Big(\theta^i(A_j) - \pi^i_j\Big)$$

means the valuation of agent i given the allocation k and its type (willingness to pay), deducting the realization cost. Therefore, i's valuation might also turn out to be negative $v^i(k, \theta^i) < 0$ for alternative A_j if $k_j = 1$ and deciding alternative A_j to be provided is a non-optimal outcome from the i's point of view.

In the context of SCF, the following desirable definitions are given, in order to fulfill several important conditions.

Definition 8.3.1. (Individual Rationality (IR)). A mechanism $D = ((\Theta^i)_{i \in N}, f(\cdot))$ fulfils the individual rationality condition once the participation can not lead to a negative utility for any agent. This condition is also known as participation constraint or voluntary participation since it enforces that no agent participating in a voluntary way can derive negative consequences by participating. Suppose that $\overline{u^i}(\theta^i)$ denotes that utility agent i derives by non-participation. Then *ex-post* individual rationality means that a SCF $f(\cdot) = (k(\cdot), t^1(\cdot), \ldots, t^i(\cdot), \ldots, t^n(\cdot))$ is individually rational if

$$u^i(f(\theta^i, \theta^{-i}), \theta^i) \geq \overline{u^i}(\theta^i) \;\forall\; (\theta^i, \theta^{-i}) \in \Theta)$$

Besides *ex-post*, there are also *ex-ante*, and *interim* individual rationality existing, being useful concepts applicable prior participation (ex-ante) as long as an agent has not learned its own type, and amid participation (interim), after an agent has learned its own type, but before the agent has chosen any action. By means of ex-ante, interim, and ex-post individual rationality, the selfish agents decide upon the expected or derived utility if participation is *individually rational*.

Definition 8.3.2. (Allocative Efficiency (AE)). A SCF $f(\cdot) = (k(\cdot), t^1(\cdot), \ldots, t^i(\cdot), \ldots, t^n(\cdot))$ is called allocatively efficient (or pareto-efficient) if its allocation K maximizes the *social welfare* based on the agents' types $(\theta^1, \ldots, \theta^i, \ldots, \theta^n) = \theta \in \Theta$

$$k(\theta) \in \arg\max_{k \in K} \sum_{i=1,\ldots,n} v^i(k, \theta^i)$$

where the *social welfare* is the sum of the agents' valuations, which is to be maximized. Put differently, an allocation is then efficient, once it maximizes the overall satisfaction with respect to all given outcomes. This might result in providing an alternative $A_j \in A$, but might especially also result in no alternative provision, i.e. $\sum_{A_j \in A} k_j = 0$ for all $k \in K$. Whenever the allocation is assumed to be optimal, an allocation k is denoted with K_*.

Ex-post efficiency then means that there does not exist any $o \in O$ such that $u^i(x, \theta^i) \geq u^i(f(\theta), \theta^i)$ for all $i \in N$ and $u^i(x, \theta^i) > u^i(f(\theta), \theta^i)$ for some $i \in N$.

Definition 8.3.3. (Budget Balance (BB)). For a given SCF $f(\cdot) = (k(\cdot), t^1(\cdot), \ldots, t^i(\cdot), \ldots, t^n(\cdot))$ *budget balance (BB)* means that the sum of payments of or to agents $t^1, \ldots, t^i, \ldots, t^n$ sum to 0

$$\sum_{i \in N} t^i(\theta) = 0$$

where $\theta \in \Theta$. In case that this sums up to 0, it is called *strict budget balance (SBB)* and once the sum of payments is less or equal to 0, it is named *weak budget balance (WBB)*, that is

$$\sum_{i \in N} t^i(\theta) \leq 0$$

If the SCF is neither *weakly budget balanced* nor *strict budget balanced*, it is named *not budget balanced*, i.e. $\sum_{i \in N} t^i(\theta) > 0$.

As long as a SCF is *weakly* or *strictly budget balanced*, the monetary inflow is generally sufficiently and the surplus is required to be allocated. Once the SCF is not *budget balanced*, there is a surplus outstanding that needs to be compensated by an external party.

Definition 8.3.4. (Incentive Compatibility (IC)). The definition of incentive compatibility (IC) was first introduced by Hurwicz (1973), while the used notation is aligned to Narahari (2013). The incentive compatibility describes mechanisms where truth-telling is a dominant strategy, meaning that selfish behavior is explicitly desired. If a direct mechanism $D = ((\Theta^i)_{i \in N}, f(\cdot))$ implements a SCF $f(\cdot) = (k(\cdot), t^1(\cdot), \ldots, t^i(\cdot), \ldots, t^n(\cdot))$, if it is incentive compatible if there is a *pure strategy equilibrium*

$$s_*(\cdot) = (s_*^1(\cdot), s_*^i(\cdot), s_*^n(\cdot))$$

where $s_*^i(\theta^i) = \theta^i, \forall : \theta^i \in \Theta^i, : \forall : i \in N$ ($s_*^i(\cdot)$ means an equilibrium strategy of agent i.

Further, the *dominant strategy incentive compatibility* (DSIC) is defined in the same way as the incentive compatibility (IC) with the difference that a weakly dominant strategy equilibrium holds, i.e.

$$u^i(f(\theta^i, \theta^{-i}), \theta^i) \geq u^i(f(\theta^i_\prime, \theta^{-i}), \theta^i)$$
$$\forall \theta^i \in \Theta^i, \forall \theta^{-i} \in \Theta^{-i}, \forall \theta^i_\prime \in \Theta^i_\prime, \forall \theta^{-i}_\prime \in \Theta^{-i}_\prime$$

where $\theta^i_\prime$ means an untrue type of agent i, that is especially $\theta^i_\prime \neq \theta^i$.

A mechanism fulfilling the stronger form, i.e. dominant strategy incentive compatibility, is also called *truthful* or *strategy-proofed*. In such a situation, reporting true types is incentivized and aligned with the overall incentive schema.

8.3.4 The Vickrey-Clarke-Groves Mechanism

The afore-mentioned definitions *individual rationality (IR)*, *allocative efficiency (AE)*, *budget balance (BB)*, and *incentive compatibility (IC)* can be interpreted as attributes of mechanisms and produced solutions for these problems. According to the theorem of Hurwicz (1973), mechanisms satisfying allocative efficiency and (strict) budget balance simultaneously in a strategy-proofed mechanism is not possible. Rather more, conditions need to be relaxed, that is why the family of VCG mechanisms satisfy the mentioned condition, except (strict) budget balance, i.e., there is a need to add additional money to get the mechanism working. VCG mechanisms are strategy-proofed, i.e. truth-telling is a dominant strategy (dominant strategy incentive compatibility (DSIC)). Further, the mechanisms are ex-ante individually rational (IR) and allocative efficient (AE). The mechanism is known as Groves mechanism and follows the general form

$$t^i(\theta) = \left[\sum_{j \neq i} v^j(k(\theta), \theta^j)\right] - h^i(\theta^{-i}) \ \forall \ i = 1, \ldots, n$$

where $h^i(\theta^{-i})$ is known as a function $h^i : \Theta^i \to \mathbb{R}$ that needs to be implemented. The former part is known as the Groves theorem and the latter part is an arbitrary function. The function $t^i : \Theta \to \mathbb{R}$ is meant to be a payment rule of agent i on the basis of a type profile Θ, resulting in the (side) payment of or to an agent. The function $h^i(\cdot)$ can be implemented by the Clarke (Pivotal) mechanism by

$$h^i(\theta^{-i}) = \left[\sum_{j \neq i} v^j(k^{-i}(\theta^{-i}), \theta^j)\right] \ \forall \ i = 1, \ldots, n$$

This function given, the monetary transfer of or to agent i is calculated by the valuation of all other agents $j \in N, i \neq j$ under an efficient allocation where i is present minus the valuation of all other agents $j \in N, i \neq j$ under an efficient allocation where i is **not** present. The difference between both terms can be interpreted as the marginal contribution of agent i to the system. Such a function is aligned along the agent's incentives, e.g. the payout is increased once the system's overall valuation is increased. Because each agent is assumed to be rational and selfish, it is therefore indirectly incentivized to increase the systems's overall valuation, too.

8.4 Numerical Example

The out-stated model and the introduced VCG mechanism are illustrated by a numerical example. The numerical example illustrates the behavior of a strategy-proofed mechanism, the VCG, in a multi-criteria problem setting, while considering the conditions individual rationality, dominant strategy incentive compatibility, and allocative efficiency. As usual for the family VCG, the outcome can not be guaranteed to be budget-balanced.

For illustrating purposes, the use case is based on the common good in general, and the forestry more specific and without any loss of generality. To keep the use case as simple as possible and as complex as needed to illustrate its social and economic implications especially with respect to a multi-criteria setting, there are three alternatives assumed to be existing $A = \{A_1, A_2, A_3\}$, each of them might be and is not required to be part of the final outcome $o \in O$. The good is held by owner p, who makes the alternatives A available. Table 8.1 contains the numerical representation of the alternatives the agents decide over, that is introduced as a matrix X above. That way, the alternatives $A_1, A_2, A_3 \in A$ are mentioned row-wised while the alternatives are described numerically column-wise by means of the criteria $C_1, C_2, C_3 \in C$. The last column π_j shows the realization cost associated with each alternative $A_j \in A$ (the cost needed to pay to provide this alternative). As mentioned, owner p declares these alternatives' costs and receives the realization cost of that alternative that have been decided by the agents. In this setting, the Table 8.1 contains already normalized manifestations for each criterion at each alternative such that the manifestations sum up to 1 row-wise. Another insight is given with Figure 8.1, illustrating the differences between these alternatives in a graphical way.

	C_1	C_2	C_3	π_j
A_1	0.363636	0.090909	0.545455	45
A_2	0.545455	0.363636	0.090909	50
A_3	0.363636	0.545455	0.090909	55

TABLE 8.1: Numerical representation of the alternatives

Such a table with relative numerical operationalization of alternatives in a multi-criteria setting might be the result of incorporating diverging judgements across agents being involved in a group decision-making process. For example, one existing and quite popular methodology to use Multi-Criteria Decision Analysis (MCDA) in groups is given by Analytic Hierarchy Process (AHP) (Velasquez and Hester, 2013b; Saaty and Vargas, 2012), whose alternatives are described in the same way. In AHP, decision-makers are asked by pairwise-comparison to derive the manifestations for the criteria as long as they does not exist in advance - then the resulting manifestations represent the subjective perceptions of the decision-makers (the numerical representation might also be derived from elsewhere).

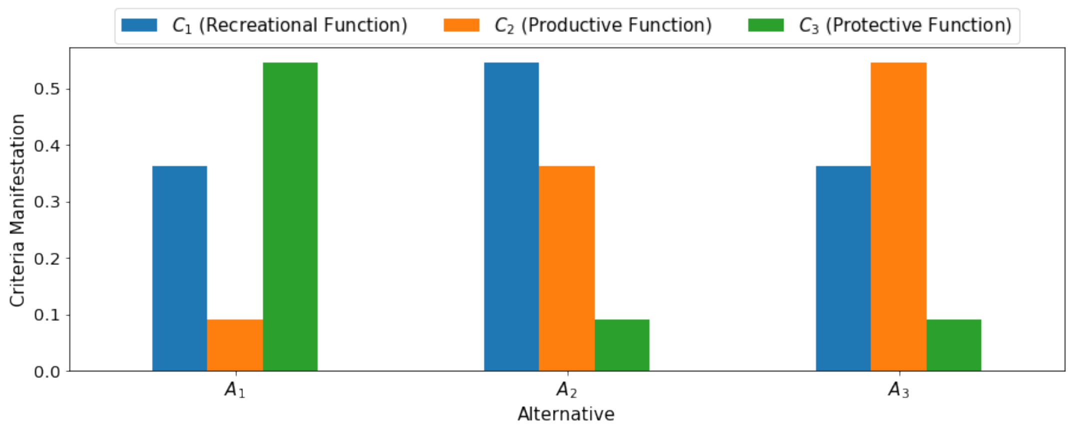

FIGURE 8.1: Numerical representation of the alternatives

To make the example more illustrative, the following explanations associate the used criteria $C_1, C_2, C_3 \in C$ with linguistic variables that fit the use case of the example at best. Following this, C_1 represents the *recreational function*, C_2 the *productive function*, and C_3 the *protective function*. This classification was already used in the introduction and is typical for goals in the forestry (Hanewinkel, 2011). This classification can be reused at this point as it illustrates the conflicting goals in an intuitive way. According to this criteria, alternative A_1 represents a profoundly low productive function while keeping very high the protective function. Consequently, the recreational function is high as well but lower compared to the protective function as, for some regions, any intervention is to be prevented. With respect to alternative A_2, the recreational function dominates other functions, but not in a strong way. In more detail, the productive function is less far behind the recreational function, which has a small distance to the protective function. Lastly, alternative A_3 lies to focus on the productive function while the recreational and the protective function are far behind. It needs to be mentioned that the manifestations for the criteria $C_1, C_2, C_3 \in C$ are, in a more narrower sense, arbitrarily derived. The focus is not on scientifically carefully derived manifestations for each criteria, which are most representative for the forest industry, but rather they answers the purpose of providing an illustrative example of a common good.

Beyond the alternatives $A_1, A_2, A_3 \in A$ and the criteria $C_1, C_2, C_3 \in C$ describing the alternatives, there are three agents $N = \{1, 2, 3\}$ in the decision involved. Each of these three agents is assumed to be rational and selfish, that is they try to maximize their individual utility. The agents are further assumed to have diverging preferences over the criteria. Between these agents information asymmetry is given, therefore no agent owns information about the each other. This is why each agent is faced with uncertainty about the other agents' types.

	Agent 1	Agent 2	Agent 3
w_1^i	0.333333	0.166667	0.500000
w_2^i	0.500000	0.333333	0.166667
w_3^i	0.333333	0.500000	0.166667
θ^i	15	20	25

TABLE 8.2: The agents' preferences over criteria

Table 8.2 depicts the diverging preferences of the agents $1, 2, 3 \in N$ over the above introduced criteria $C_1, C_2, C_3 \in C$. For this purpose and as introduced before, w_k^i depicts the weight for criteria C_k of agent i. The last row depicts the willingness to pay θ^i (the type) of each agent i. In this example, the type set is $\Theta = \{0, 5, 10, 15, 20, 25\}$, each agent can choose one from $\theta^i \in \Theta$. According to Table 8.2, the true type profile for this example is $\theta = (\theta^1 = 15, \theta^2 = 20, \theta^3 = 25)$. Figure 8.2 shows this distribution of preferences in a more graphical way. As can be seen that the preference of agent 1 is more aligned to the protective function, followed by the recreational function and then by the productive function. That way, agent 1 might eventually be an environmentalist. Agent 2 has the highest at recreational function, followed by productive function and protective function - hence, agent 2 might eventually be a hiker or biker who values the experience offered by a forest.

The last agent, agent 3, mostly prefers the productive function, followed by the recreational function and the protective function. That way, agent 3 might eventually be someone with high timber demand, for example for heating or building purposes. People working in the wood-processing industry might also be candidates with similar looking profiles. With these profiles in mind, agents with diverging preferences over the given alternatives are given.

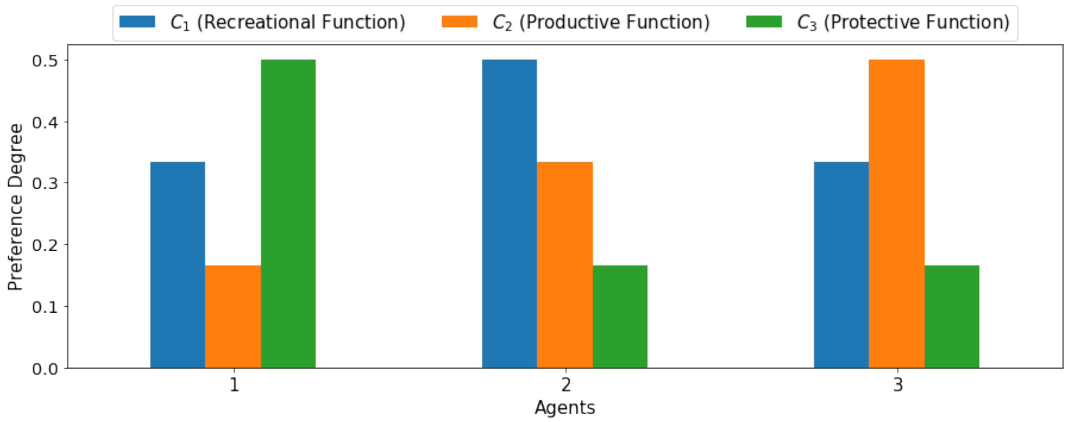

FIGURE 8.2: The agents' preferences over criteria

On the basis of the alternatives and its numerical descriptions operationalized to criteria manifestations shown in Table 8.1 and the agents with their preferences to these criteria and their corresponding type θ^i (the willingness to pay) shown in Table 8.2, the values shown in Table 8.3 can be derived. The values of Table 8.3 show for each agent i and each alternative A_j the part-worth utilities of the criteria $k = 1, \ldots, 3$ (that is $\beta^i_{j,1}$, $\beta^i_{j,2}$, $\beta^i_{j,3}$) for the corresponding agent and alternatives, the overall non-monetary utility y^i_j of agent i for alternative A_j, the normalized ratio each alternative achieves (the best alternative is assigned a 1 to be mostly preferred), and finally the adjusted willingness to pay θ^i_j, that is the type of each agent i for an alternative A_j. As can be seen that the maximal willingness to pay for each agent lies at the most preferred alternative with highest non-monetary utility y^i_j. That way, an alternative that is most preferred by MCDA is associated with its preferences over the criteria (put differently, the alternative that is mostly preferred on the basis of a given preference with respect to all criteria is associated with the non-reduced and maximal willingness to pay and any other type is interpolated according the ratio derived by the MCDA non-monetary utilities).

i	A_j	$\beta^i_{j,1}$	$\beta^i_{j,2}$	$\beta^i_{j,3}$	y^i_j	$\frac{y^i_j}{\max_{A_j \in A} y^i_j}$	θ^i_j
1	A_1	0.121	0.015	0.273	0.409	1.000	15.000
1	A_2	0.182	0.061	0.045	0.288	0.704	10.556
1	A_3	0.121	0.091	0.045	0.258	0.630	9.444
2	A_1	0.182	0.030	0.091	0.303	0.741	14.815
2	A_2	0.273	0.121	0.015	0.409	1.000	20.000
2	A_3	0.182	0.182	0.015	0.379	0.926	18.519
3	A_1	0.121	0.045	0.091	0.258	0.630	15.741
3	A_2	0.182	0.182	0.015	0.379	0.926	23.148
3	A_3	0.121	0.273	0.015	0.409	1.000	25.000

TABLE 8.3: Agents' part-worth utilities, non-monetary utilities and types (willingness to pay)

8.4.1 Determination of Allocations

After the cost π_j for each alternative $j = 1, \ldots, m$ is known and the agents $i = 1, \ldots, n$ have determined their types (according to their private information) θ^i_j for each alternative $j = 1, \ldots, m$, each agent reports its type to the social choice function to let solve the *preference aggregation problem*. For this purpose, the reported types are denoted with $\widehat{\theta} = (\widehat{\theta}^1 = 15, \widehat{\theta}^2 = 20, \widehat{\theta}^3 = 25)$ (the reported type must not necessarily be the true type and over- or underestimation might be an choice for each agent). The social choice function is then called $f((\widehat{\theta}^1 = 15, \widehat{\theta}^2 = 20, \widehat{\theta}^3 = 25))$ and produces an output (including an allocation and the the payments for or to the agents) $(k(\widehat{\theta}), t^1(\widehat{\theta}), \ldots, t^i(\widehat{\theta}), \ldots, t^n(\widehat{\theta})) \in O$.

i	A_j	π_j	π^i_j	$\widehat{\theta}^i_j$	k_j	v^i_j	t^i_j	u^i_j
1	A_1	45	15.00	15.00	0.0	0.00	0.00	0.0
1	A_2	50	16.67	10.56	1.0	-6.11	9.81	3.7
1	A_3	55	18.33	9.44	0.0	0.00	0.00	0.0
2	A_1	45	15.00	14.81	0.0	0.00	0.00	0.0
2	A_2	50	16.67	20.00	1.0	3.33	0.37	3.7
2	A_3	55	18.33	18.52	0.0	0.00	0.00	0.0
3	A_1	45	15.00	15.74	0.0	0.00	0.00	0.0
3	A_2	50	16.67	23.15	1.0	6.48	-2.78	3.7
3	A_3	55	18.33	25.00	0.0	0.00	0.00	0.0

TABLE 8.4: Outcome of the social choice function

The allocation and side payments achieved are summarized in Table 8.4. The table contains for each agent i and each alternative j the individual cost π^i_j, the reported type $\widehat{\theta}^i_j$, the resulting allocation k_j, the resulting valuation v^i_j, the side payments t^i_j, and the final utility u^i_j. As shown by Figure 8.3, the social welfare for alternative A_2 is the maximum among the given alternatives and positive. This is why this alternative is allocated. The valuation for non-allocated alternatives is actual zero (as shown in Table 8.4) but for the aid of understandability, Figure 8.3 illustrates in an if-then scenario the social welfare if it would come to an allocation. According to Figure 8.3, alternative A_2 maximizes the social welfare and is therefore chosen. The social welfare of alternative A_1 is also positive but not far enough compared to alternative A_2. For the sake of completeness, alternative A_3 reaches negative social welfare and would never be chosen, even if no other alternative would be present, since it would yield negative utility (social welfare) in total.

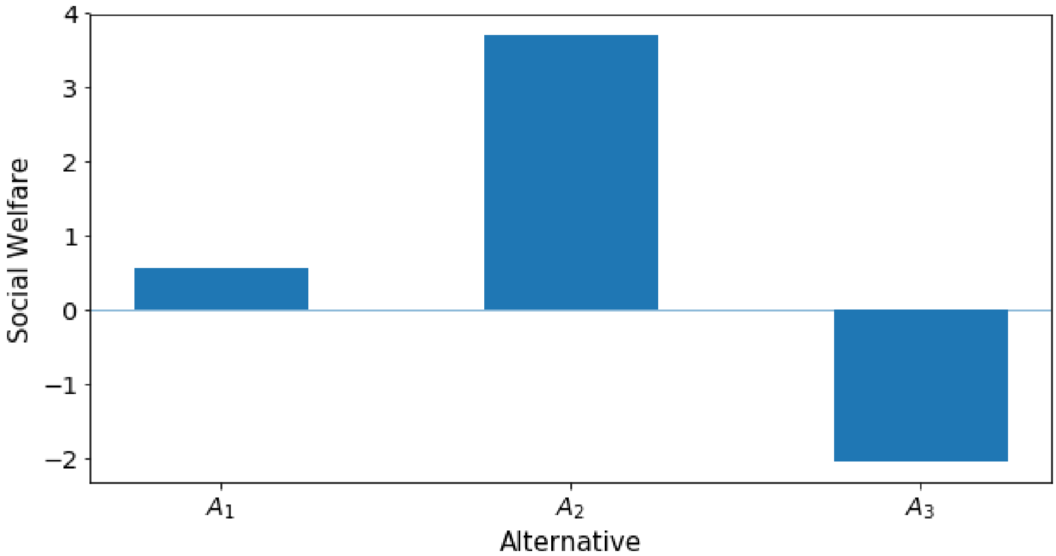

FIGURE 8.3: Social welfare for each alternative

The valuations of the agents, regardless which alternative was decided, are for agent $i = 1$ given with $v_1^1 = 0$, $v_2^1 = -6.11$, $v_3^1 = -8.89$, for agent $i = 2$ given with $v_1^2 = -0.19$, $v_2^2 = 3.33$, $v_3^2 = 0.19$, and for agent $i = 3$ given with $v_1^3 = 0.74$, $v_2^3 = 6.48$, $v_3^3 = 6.67$.

When taking the values of agent 1 into account, it is obvious that the valuation is negative. This can be attributed to the fact that agent 1 has a strong preference for the protective function, but the protective function has a low manifestation in alternative A_2 (alternative A_3 has an even lower manifestation for this criteria). The most preferred alternative for agent 1 would be alternative A_1 since its valuation achieves there its maximum. Considering the situation of agent 2, its most preferred alternative is A_2 with $v_2^2 = 3.33$. Because this is also the alternative that was chosen, its need is fulfilled as best as possible. The most preferred alternative of agent 3 is alternative A_3, but this alternative does not maximize the overall social welfare - moreover, this alternative yields negative social welfare.

It can be noticed that the sum of all side payments is $\sum_{i \in N} t^i = 9.81 + 0.37 - 2.78 = 7.4$. Therefore, there is more money required (+7.4) as necessary to settle the cost ($\pi^2 = 50$) incurred by the decision being part of the outcome. This additional money is used to let it a weakly dominant strategy for each agent to report truthfully.

8.4.2 Agents' Strategy Analysis

Since the given allocation was produced by a new implementation of a mechanism belonging to the VCG family, in this sub section a simulative approach is used to illustrate that the introduced constraints hold, i.e. the incentive compatibility constraint, the allocative efficiency constraint, and the individual rationality constraint. As already explained before, it is common sense that the budget balance constraint can not necessarily be held.

For this purpose, the strategy (type) set for each agent was partly enumerated. With help of this enumeration, the behavior and its consequences of each choice can be observed. The type set for each agent i is defined as $\Theta^i = \{0, 5, 10, 15, 20, 25\}$. Hence, each element $\theta^i \in \Theta^i$ was validated to be non-increasing the final utility at the end. To check each type for each agent, there were $6 \times 3 \times 3 = 54$ iterations necessary ($|\Theta^i| = 6$ types, 3 alternatives, and 3 agents). When the simulative approach changes the announcements of one agent $i \in N$, then all other agents $1, \ldots, -i, +i, \ldots, n \in N$ remain unchanged.

The Figures 8.4, 8.5, 8.6 illustrate the respective outcomes for these simulations. Each figure shows the value in the ordinate and the signaled willingness to pay (the type) in the abscissa. The value refers to a monetary unit, e.g. the valuation or the utility. Signals refer to the reported type of an agent. The vertical solid black line depicts the true type of the corresponding agent with respect to the alternative the figure belongs to while the vertical dotted black line depicts the type that belongs to the agent's preferences on the level of criteria (the dotted line is the same for each agent across all alternatives since it is independent of any alternative). Furthermore, the green line shows the monetary unit of the valuation in relation to the signaled type and the red line shows the monetary unit of the utility in relation to the signaled type. Both the red and the green solid line are accompanied by dotted lines that illustrate the resulting signaled / reported valuation or utility. The lines diverge because each agent might have a true type (private information) on the one hand and a signaled type (that differs potentially) on the other hand, which is made public by the agent. If the agent signals a higher valuation or utility, that does not necessary means an increase in the true valuation or utility. Whenever an asterisk is mentioned after the used signal in the abscissa, it means that the alternative the figure belongs to was allocated (chosen).

First, agent 1 prefers the protective function, then the recreational function, and then the protective function. The alternative that increases that agent's utility is alternative A_1, followed by alternative A_2, and alternative A_3 (see Table 8.3 and Table 8.4). The agent is therefore interested in an allocation where alternative A_1 is determined. The results of the simulation are summarized by Table 8.5. The table shows the alternative A_j and if this alternative was allocated k_j, the reported type $\widehat{\theta}^i_j$, the valuation v^i_j and the utility u^i_j according this reported type, and the side payment to or of agent i. The column θ^i_j depicts the agent's true type and $truev^i_j$ and $trueu^i_j$ the actual valuation and utility of agent 1. By this data, information can be derived regarding whether it is worth over- or underestimating preferences. The Figures 8.4 illustrate this information in a visual way.

As the red and green lines for alternative A_1 indicate, there is no change from utility 3.70 and valuation -6.11 anywhere from 0 to 15, both for the true and the signaled utility (the dotted and the solid line overlap). Apart from the fact that it can not increase the utility if the agent reduces its willingness to pay for an alternative that promises highest utility for that agent. From this viewpoint, the agent would need to report a higher willingness to pay than its true willingness to pay. This happened with type $\widehat{\theta^i} = 20$ where the agent get alternative A_1 allocated by overestimating its type by 5 ($20 - 5 = 15$). That way, with the aid of signal 20, the agent had success to get alternative A_1 to be allocated (the asterisk immediately behind 20 in the abscissa). Nevertheless, once the wished alternative A_1 got allocated, the side payment to agent 1 is reduced from 9.81 to 0.55 as indicated by the solid red line. After this reduction, it does not appeal very attractive to agent 1 to overestimate a higher type than its true type (to act strategically or to report untruthfully). This is also true for reporting $\widehat{\theta^i} = 25$. As can further be seen that the dotted red line (the reported utility) increases since a higher willingness to pay (type) also imply a higher valuation and / or utility.

A_j	k_j	$\widehat{\theta^i_j}$	v^1_j	u^1_j	t^1_j	true θ^1_j	true v^1_j	true u^1_j
1	0	0-15	-6.11	3.70	9.81	15.00	-6.11	3.70
1	1	20	5.00	5.56	0.56	15.00	0.00	0.56
1	1	25	10.00	10.56	0.56	15.00	0.00	0.56
2	0	0-5	0.00	0.56	0.56	10.56	0.00	0.56
2	1	10	-6.67	3.15	9.81	10.56	-6.11	3.70
2	1	15	-1.67	8.15	9.81	10.56	-6.11	3.70
2	1	20	3.33	13.15	9.81	10.56	-6.11	3.70
2	1	25	8.33	18.15	9.81	10.56	-6.11	3.70
3	0	0-15	-6.11	3.70	9.81	9.44	-6.11	3.70
3	1	20	1.67	8.52	6.85	9.44	-8.89	-2.04
3	1	25	6.67	13.52	6.85	9.44	-8.89	-2.04

TABLE 8.5: Simulation results for agent $i = 1$

With respect to alternative A_2, the agent $i = 2$ might be interested in reducing its type to prevent A_2 from determining, because the agent prefers alternative A_1. As shown, reporting a type $\widehat{\theta^1_2} < 10.56$ as underestimation strategy to prevent the alternative from allocation, would not be successfully as the true u^1_2 is 0.56 for $\widehat{\theta^1_2} \in \{0, 5\}$ and 3.7 for $\widehat{\theta^1_2} = 10$. It is obvious that 3.7 is the maximal utility the agent can derive, therefore it is a weakly dominant strategy to the agent to neither do over- nor underestimation. Alternative A_3 is worse from the agent's 1 view point, therefore underestimation might be a report. There can no difference be seen from $\widehat{\theta^1_3}$ for 0 -

15. While the true type is $\theta_3^1 = 9.44$ for A_3 and the maximum in the true u_j^i is 3.7 from $0 \leq \widehat{\theta}_3^1 \leq 15$, it is not worth over- or underestimating its private type for A_3.

A_j	k_j	$\widehat{\theta}_j^2$	v_j^2	u_j^2	t_j^2	true θ_j^2	true v_j^2	true u_j^2
1	0	0-15	3.33	3.70	0.37	14.81	3.33	3.70
1	1	20	5.00	5.74	0.74	14.81	-0.19	0.56
1	1	25	10.00	10.74	0.74	14.81	-0.19	0.56
2	0	0-15	-0.19	0.56	0.74	20.00	-0.19	0.56
2	1	20	3.33	3.70	0.37	20.00	3.33	3.70
2	1	25	8.33	8.70	0.37	20.00	3.33	3.70
3	0	0-20	3.33	3.70	0.37	18.52	3.33	3.70
3	1	25	6.67	4.44	-2.22	18.52	0.19	-2.04

TABLE 8.6: Simulation results for agent $i = 2$

The simulation results for agent $i = 2$ are contained by Table 8.6 and Figure 8.5. Agent 2 has its focus on recreational function, then productive function, and then protective function. With this preferences in mind, agent's 2 most preferred alternative is A_2, as shown by Table 8.3. In general, since agent 2 prefers alternative A_2, it might be selfish to overestimate the type for alternative A_2 and to underestimate the type for the others. The data accompanied by the visualizations show that for alternative A_1 there is no change until its reported type reaches $\widehat{\theta}_1^2 = 15$. Because its true type for A_1 is $\theta_1^2 = 14.81$, there is no additional utility for agent 2 by underestimation its type. Clearly, overestimating its type is also non-optimal for agent 2 because alternative A_1 is not preferred. This is supported by the observation that the final outcome turns out to be $u_1^2 = 0.56$ for overestimation, lower than truthful reporting leads to. For alternative A_2, agent 2 reaches its maximum in its utility $u_j^2 = 3.7$. It can never be observed an utility that is higher; that way, it is a weakly dominant strategy to report truthfully. Alternative A_3 is also worse for agent 2, therefore underestimation might be an strategy - when it comes to underestimation, the final utility for agent 2 turns out to be 3.7, since it comes not to an allocation for this alternative. Even if agent 2 report a type $\widehat{\theta}_3^2 = 25$, the agent changes the allocation in favor of alternative A_3. Because alternative A_3 is not preferred (as also valid for alternative A_1, this can not be selfish by agent 2).

The last agent, agent $i = 3$, put its focus on the productive function, the recreational function, and the protective function (in this order). Agent 3 is therefore be interested in alternative A_3 and derives its maximal utility from it. With respect to the first alternative A_1, agent 1 manages this alternative to get allocated by overestimating its type $\widehat{\theta}_1^3$ to 20 or 25. But there is not need to overestimate since alternative A_1 is non-optimal for agent 3. It might be make sense to underestimate to let the alternative non-allocated, but the final result is not effected by this. For alternative A_2, agent 2 is also faced with a non-optimal alternative. Therefore, underestimating its type would make sense, but its final utility is not increased by this. The last alternative, alternative A_3, is the most preferred alternative for agent 3, but this alternative can not be allocated, whatever agent 3 reports. Therefore, as Table 8.7 indicate, the highest utility agent 3 can derive is $u_j^3 = 3.7$. This utility can be achieved by reporting truthfully and no higher utility can be achieved by reporting untruthfully. That way, it is also for agent 3 a weakly dominant strategy to report truthfully.

A_j	k_j	$\widehat{\theta}_j^3$	v_j^3	u_j^3	t_j^3	true θ_j^3	true v_j^3	true u_j^3
1	0	15	6.48	3.70	-2.78	15.74	6.48	3.70
1	1	20	5.00	4.81	-0.19	15.74	0.74	0.56
1	1	25	10.00	9.81	-0.19	15.74	0.74	0.56
2	0	15	0.74	0.56	-0.19	23.15	0.74	0.56
2	0	20	0.00	0.00	0.00	23.15	0.00	0.00
2	1	25	8.33	5.56	-2.78	23.15	6.48	3.70
3	0	25	6.48	3.70	-2.78	25.00	6.48	3.70

TABLE 8.7: Simulation results for agent $i = 3$

Because the simulations of Table 8.5, 8.6, and 8.7 and Figures 8.4, 8.5, and 8.6 are restricted to the sub set of all combined types possible, Figure 8.7 shows the application of the entire combined types. As can be seen, for agent $i = 1, \ldots, 3$, that no choice of combinations can lead to a higher utility than the true combination leads to. Each of these three figures follows the same structure. The structure of each figure of Figure 8.7 has the monetary unit as value in the ordinate and the used combination of types for this agent in the abscissa. Due to space restrictions, the special combinations are not enumerated explicitly. Each combination consists of a three-dimensional vector $(type_1^i, type_2^i, type_3^i)$ for each agent $i = 1, \ldots, 3$. Each type for one alternative. Due to $|\Theta^i|^3$, the number of all combinations used is 216 (the number of x-values in the abscissa). Each figure contains three filled lines: the actual u_j^i as the utility of agent i for alternative j, the u_j^i as publicly known utility the agent's report of its types belongs to, and the resulting payment of or to the agent t_j^i. The horizontal dotted black line illustrates the true utility when agent i reports truthfully. That way, it is a weakly dominant strategy for each agent to report truthfully.

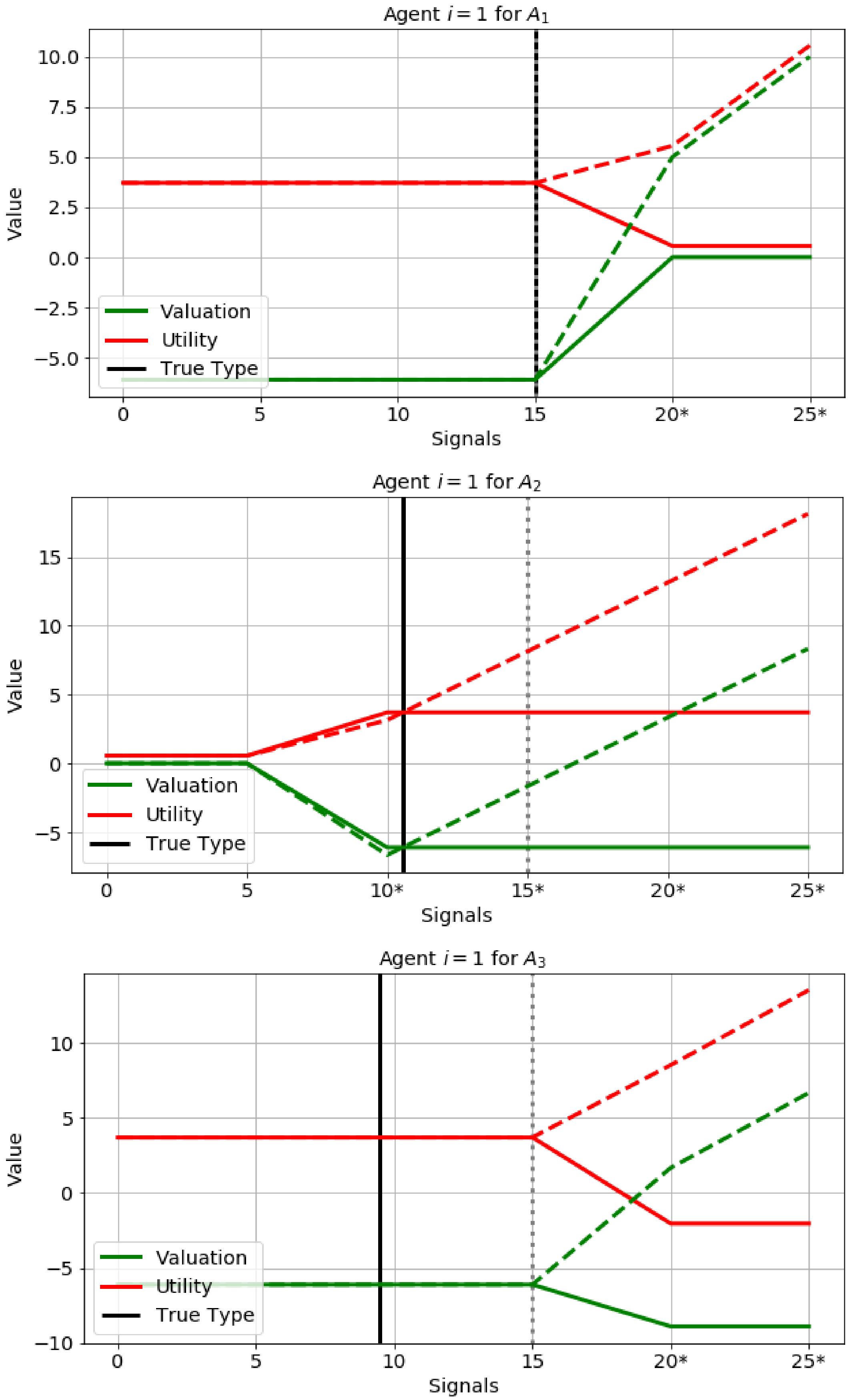

FIGURE 8.4: Type enumeration for agent 1 and alternatives A_1, A_2, A_3

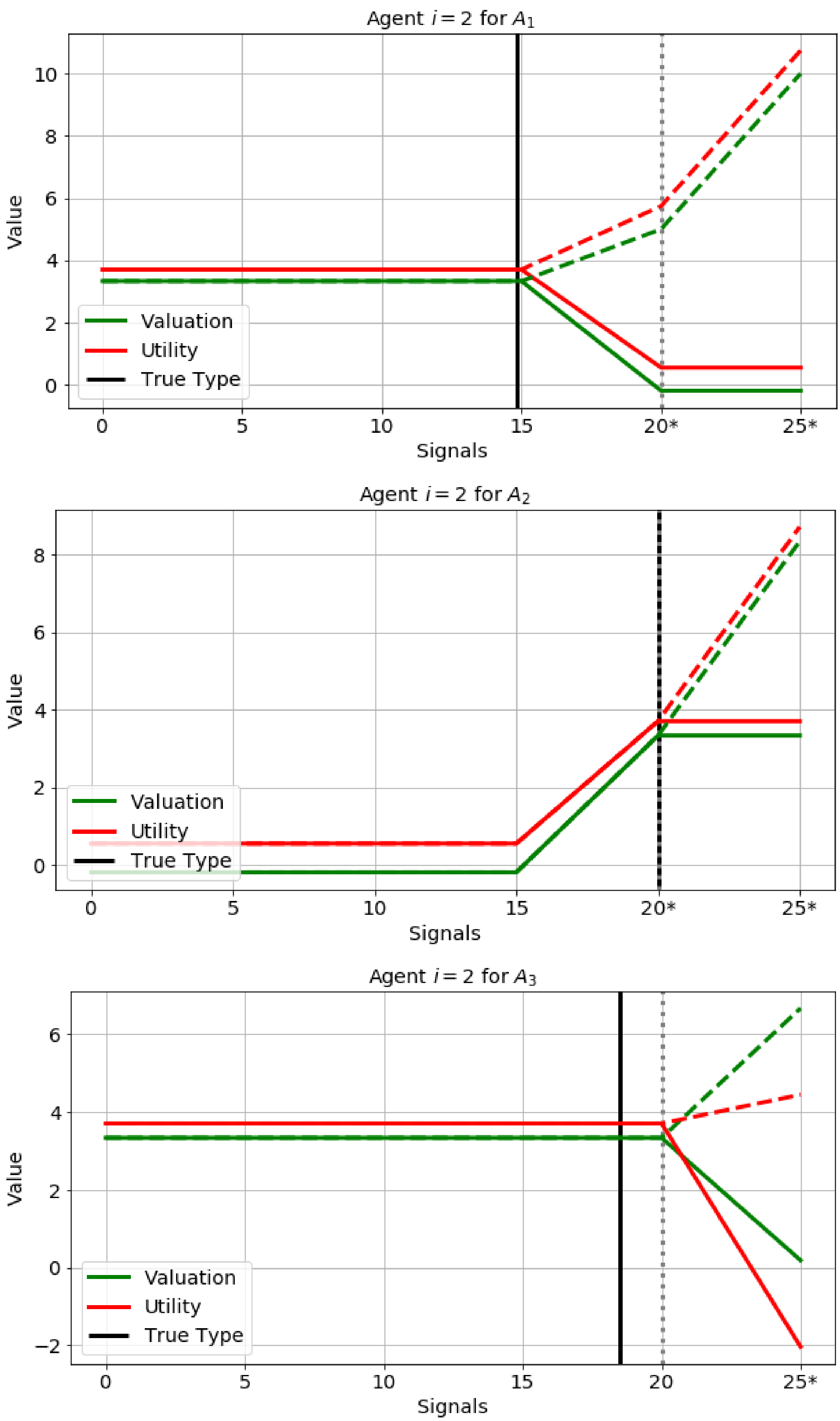

FIGURE 8.5: Type enumeration for agent 2 and alternatives A_1, A_2, A_3

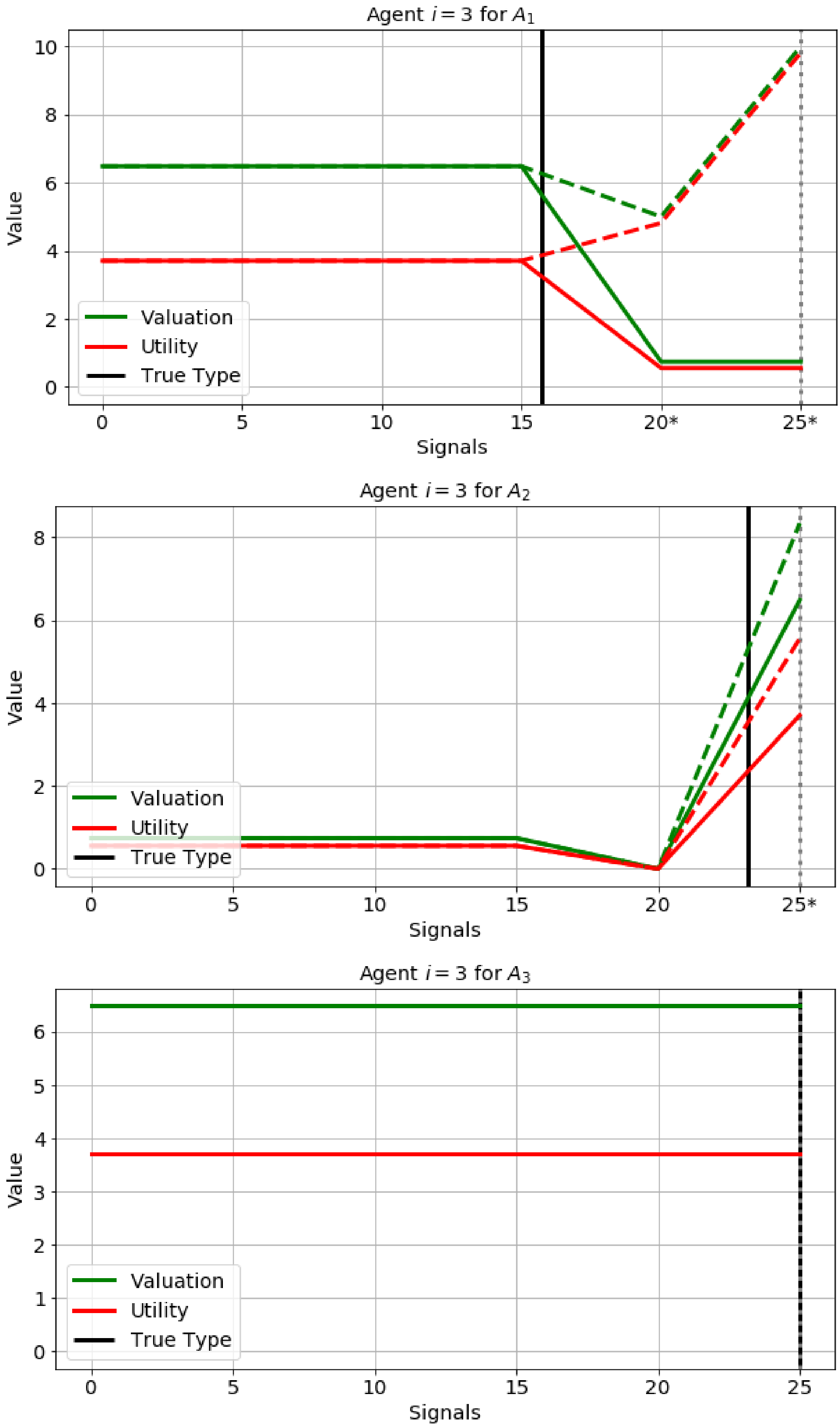

FIGURE 8.6: Type enumeration for agent 3 and alternatives A_1, A_2, A_3

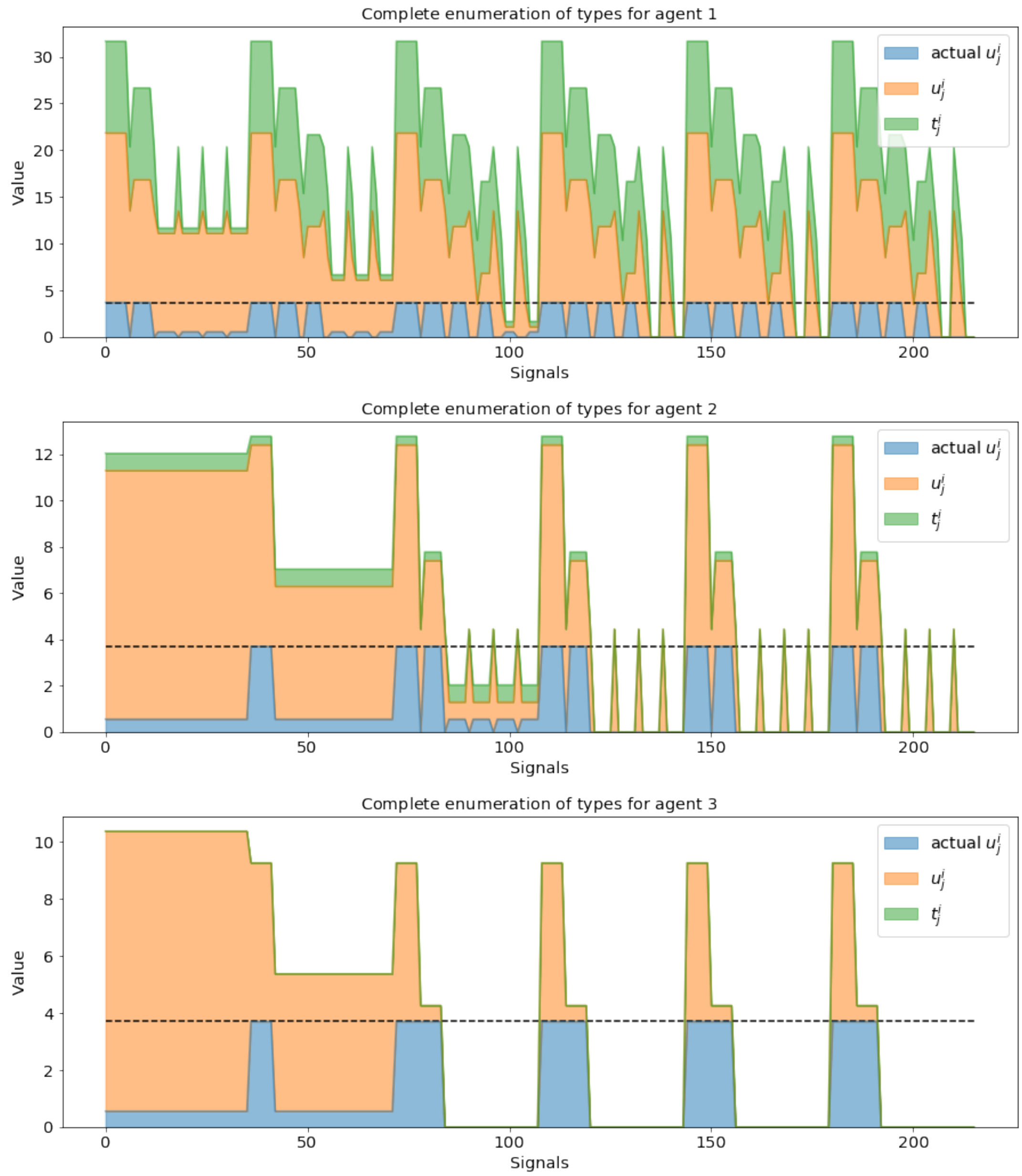

FIGURE 8.7: Complete simulation of types for agents $i = 1, 2, 3$

8.5 A Model for Smart Contracts

In the world of blockchain, complex computer programs are implemented by means of smart contracts, which are distributed across the nodes and executed locally. Smart contracts are deterministic programs because their input and output must be consistent among themselves, meaning that the state before and after each execution needs to be the same for each node. Smart contracts can specify and implement programs as theoretically elaborated in this work. They can define suitable type sets (willingness to pay) for the participating users, which can be emitted. The conceptualized social choice functions, the side payments of VCG, and other parts of the mechanism can be implemented and executed automatically. Programming languages for smart contracts, for instance Solidity for Ethereum (Bennington, 2017), become more and more mature (Bartoletti and Pompianu, 2017; Chatterjee, Goharshady, and Velner, 2018), and can implement such models as the proposed one. The specification, which needs to be defined and which is implemented afterwards, can be designed with tokens. The field of token economy and cryptocurrencies also gained much popularity over the last years. Different kinds and functions of tokens were established, for example utility tokens for specific purposes, asset tokens representing real world assets, or security / equity tokens behaving similar to a share of a company (Burnie, Burnie, and Henderson, 2018), while the differences between these are not always clear (Bennington, 2017). For the proposed model, tokens are either required to enable the participants to express their willingness to pay according to the predefined type set Θ, or required to assign the voting power to those participants that are eligible to do so. When it comes to implementation, it must be considered that blockchains can be private, public, or consortium based (Berryhill, Bourgery, and Hanson, 2018; Hjalmarsson et al., 2018; Hjalmarsson et al., 2018), which has an impact on the block time (private and consortium based blockchains might be faster since they could have a fewer number of trusted nodes). Today, fast block processing is still a bottleneck for e-voting with a possible high number of ballots / participants.

8.6 Conclusion

The presented work shows – to the author's best knowledge – how the public good problem can be approached by MCDA. Since the forest management problem is approached by participatory multi-criteria decision analysis, multiple participants are involved in the decision-making. Due to the non-excludability condition, each participant might benefit in either way by some services of the forest, e.g. biodiversity conversion, recreation, carbon capture and storage. When stated preferences are linked to willingness to pay (a monetary unit), and no participant can be excluded from consumption, these participants might deviate from truth-telling. Once participants decide to deviate from truth-telling, they affect the outcome in such a way that the accounted social welfare of each potential forest management alternative is wrong, i.e. inefficient in a economic sense. Put differently, in order to determine the correct forest management alternative that maximises the social welfare across the participants, the participants need to state their true preferences (including the willingness to pay). Consequently, the research objective is to examine different signaling strategies (deviating or not from truth-telling) in a participatory multiple-criteria decision-making over common goods, aiming at finding a mechanism that incentivizes participants to behave honestly.

Generally, involvement of participants in the planning process, exchanging information transparently, policy analysis (Ananda and Herath, 2009), and similar activities promise to increase public commitment, the acceptance of decisions, and might help to reduce distrust between all parties involved (Tanz and Howard, 1991) in the decision-making for forests. They also require generally binding, reliable, and transparent participation (Guyot, 2012; Reed et al., 2009) to increase, for instance, public commitment and acceptance for decisions (Ananda and Herath, 2009).

Since this research illustrates its applicability with the example of a forest, it especially focuses on so-called common good in a broader sense. Due to MCDA, multiple alternatives are available to be provided, over which the agents have to decide. The sketched social choice function chooses only one specific or no alternative according to the social welfare the alternatives give. This extension has implications to the social choice function and the way of how to combine MCDA research with game-theoretical public good problems. In order to achieve a parteo-efficient outcome at the end, the VCG payments make it a weakly dominant strategy for all agents to reveal their preferred alternatives and associated willingness to pay truthfully. With the aid of agent-based simulation techniques, a small example of a forest with three stereotyped participants and three stereotyped decision alternatives was constructed and illustrated. The agent-based simulation shows that, for each agent, truth-telling is a weakly dominant strategy in a MCDA setting.

The work has some limitations. For example, the work uses selfish agents in a game-theoretical sense. This assumption does not necessarily hold. Especially behavioral economics is a research area to consider the human and its real-world behavior in decision situations. Although humans do not act always in a selfish and utility-maximizing way, anyway, this research provide important knowledge to design such games and to be a template for economical experiments (with possibly behavioral emphasis). Further, the utility functions of the MCDA are chosen in a trivial manner as they all grow in a linear way. But this is just a limitation of the example and not of the methodology proposed since any MCDA methodology can be used that fulfills the environmental needs. Further research might embrace mechanisms where the problem of no budget-balance is addressed. Especially, this can be achieved by relaxing or violating the incentive compatibility (IC) condition. The latter one means that IC is not further present with a stronger degree, that is strategy-proofness (dominant-strategy-incentive-compatible (DSIC)), rather by downgrading it to a weaker degree, that is Bayesian-Nash incentive-compatibility (BNIC). Following this, there is a Bayesian Nash equilibrium where agents have expectations about the utility functions of all other agents. Therefore, a higher degree of certainty about the other agents is necessary or, put differently, the information asymmetry must be lower. Oftentimes, this turns out to be not further ex-post individual rational. Another further research could be to examine the proposed model in an experimental way, that is how act agents in a real-world setting as they are not always selfish and utility-maximizing.

Part IV

Evaluation & Insights

Chapter 9

The Added-Value of Blockchain-Based Participation

> I think that governments are going to get disrupted by the blockchain. I think in the same way that the Internet forced everyone to evolve, the Blockchain is going to change the game again.
>
> Adam Draper

Participatory decision-making involves people with their own preferences and aggregates these into one single outcome, the decision. Blockchain, also known as Distributed Ledger Technology (DLT), connects people who are – in a game-theoretical sense – assumed to be selfish and non-cooperative among themselves, together to reach an common goal, e.g. the transfer of money at Bitcoin. Thus, participatory decision-making and DLT-based features share commonalities, which are in the following discussed in the field of participatory forest policy decision making. A forest provides recreational, protection, and productive functions (Hanewinkel, 2011), and it is highly important in an ecological, an economical, and a social way (Dieterich, 1953). While several parties request different functions of a forest, the interests over these functions diverge - partly intensively. A Participatory Decision-Making System (PDMS) in the field of forestry enables people to take part in the decision-making process in order to co-decide the forest management. According to this idea, the PDMS is based on the Distributed Ledger Technology (DLT). Therefore, the PDMS inherits all dis- and advantages of the DLT, i.e., it is immutable for everyone, it stores data in a decentralized way, it is consensus driven, and transparent for everyone. Considering these advantages, it remains as an open question *to what extent, and to whom, a Participatory Decision-Making System (PDMS) gives utility and whether the Distributed Ledger Technology (DLT) add value in participation*. To answer these questions, this research focus on the the utility of participation in the field of forestry itself, but also on the utility derived from features that characterize a DLT.

9.1 Introduction

A forest management problem can be solved by incorporating diverging preferences of different stakeholders. For instance, consumers and the wood processing industry request the productive function, environmentalists are interested in protecting the nature and maintenance of sustainability and hence address protective function. Those people seeking rest in the forest, for instance enjoying the nature and doing sports in the forest (like hikers or mountain-bikers do), request the recreational function. Beyond this and especially in the forest, some people are oftentimes in the decision-making involved while other remain uninvolved, but still affected by such decision (Finley and Kittredge Jr, 2006). This situation can also be illustrated by considering the forest situation in Germany, where private owners hold forests by about 50 % of the overall forest area, while forests make up around a third of the whole area of Germany (most private owners hold small forest being smaller than 20 hectare) (UNIQUE forestry and land use GmbH, 2018). As a result, the decision power is usually quite concentrated in forest management. At this, participation in the decision-making process and exchanging information transparently (Ananda and Herath, 2009) promise to increase public commitment and the acceptance of decisions (Tanz and Howard, 1991).

Since participation involves people with own preferences, participatory decision-making involves these preferences in order to aggregate these into one single outcome. New technologies in the field of DLT share commonalities as they bring selfish people together to reach a shared common goal. But it remains an open question whether people value these DLT-features while participating on the level of different participation impacts, which is examined by both a face-to-face survey and an online survey. The final analysis follows a Multi-Criteria Decision Analysis (MCDA), and allows recommendations about optimal configurations of DLT on the level of different participation impacts.

9.2 Research Design

The research is driven by the research hypothesis that using a DLT while participating in forest management decision-making, it gives additional utility to the participants with respect to the advantages of a DLT, that is transparency, consensus driven, decentralization, and immutability – operationalized to utilities in such a way it creates an added-value.

The research was conducted with a self-made questionnaire, which starts with classic demographics shown in Table 9.1. The questionnaire was pre-evaluated by five students. Further, the questionnaire contains self-explained feature to the degree of knowledge for forest management, depicted as a five-point likert scale reaching from “nothing” to “comprehensive” knowledge with respect to the management of a forest. This feature is elicited to catch possibly existing differences among those having expertise on forest management compared to those where not.

Variable	Explanation
Birthday	The year of birth
Gender	The type of gender: male, female, diverse
Education	The level of education: Magister, Diploma, State Examination, Master, Bachelor, High-School Diploma, Vocational Education, No Education

TABLE 9.1: Demographics elicited in the questionnaire

A next feature is about the respondent's satisfaction with the current global situation of forest management. In the questionnaire, this was also a self-explained feature with a five-point likert scale reaching from "absolutely not" to "completely". This feature was elicited to give more understandability about the overall respondent's decisions in the questionnaire. The last mentioned items, that is the demographics and the last two self-explained judgments to the knowledge of forest management and the satisfaction with the current global situation of forest management, constitute the first "question group 1".

The "question group 2" is about the degree of desired participation impact on decision in the field of forest management. This feature is operationalized to linguistic manifestations with an ordinale scale. Participation is structured to (1) inform, (2) consult, (3) involve, (4) collaborate, and (5) empower (IAP2, 2014). As mentioned by IAP2 (2014), (1) information means to provide the public with balanced and objective information to assist them in understanding the problem, alternatives, opportunities and/or solutions. To (2) consult the public means to obtain public feedback on analysis, alternatives, and/or decisions. With (3) collaborate, it is meant to work directly with the public throughout the process to ensure that public concerns and aspirations are consistently understood and considered. With (4) collaboration, the authors means to partner with the public in each aspect of the decision including the development of alternatives and the identification of the preferred solution. The last activity, (5) empowerment, means to place final decision making in the hands of the public. These five mentioned activities increase in their respective impact on decisions.

The respondents are asked to rank these five afore-mentioned manifestations of participation impact in ascending order, i.e. the most preferred degree of participation impact is assigned a 1, while the least preferred degree of participation impact is assigned a 5. This question was framed by "Imagine you could decide with in the management of forests. Please put your preference for the different levels of impact from 1 (most important) to 5 (least important) in the following table.".

The "question group 3" consists of self-explained judgments to the importances of the features of a DLT. The question is introduced with "New technologies promise advantages in forest participation practice. Please evaluate the following manifestations with regard to forest participation. In the lower part of the table, please indicate whether you tend to the left or the right - starting from the middle.". The question group 3 consists of four features in total, which are derived from Sultan, Ruhi, and Lakhani (2018b) and which are mentioned in Table 9.2.

DLT feature	Explanation
Immutable	**permanent and tamper-proof**, a blockchain is a permanent record of transactions. Once a block is added, it cannot be altered. This creates trust in the transaction record.
Decentralized	**networked copies**, a blockchain is stored in a file that can be accessed and copied by any node on the network. This creates decentralization.
Consensus driven	**trust verification**, each block on the blockchain is verified independently via a Consensus models which provide rules for validating a block, and often use a scarce resource (such as computing power) to show proof that adequate effort was made. In Bitcoin, this is referred to as the mining process. This mechanism works without the use of a central authority or an explicit trust-granting agent.
Transparent	**full transaction history**, since the blockchain is an open file, any party can access it and audit transactions2. This creates provenance under which asset lifetimes can be tracked.

TABLE 9.2: DLT features according to Sultan, Ruhi, and Lakhani (2018b)

Since each of these features is a bit technical and non-framed to the forestry, the features are translated in a more understandable way and framed to the forestry. The first DLT feature "immutable" is left unchanged and framed by "The knowledge around the forest is not mutable. Each change are traceable additions.". The DLT feature "decentralized" is translated to "Shared knowledge" and is framed to "The knowledge around the forest is shared. Each owns an own copy. The system ensures that the knowledge is updated automatically.". The DLT feature "Consensus driven" is translated to "Trustworthiness" as it ensures that new blocks are added independently neither anyone is able to centralize power nor anyone can control anything on its own. This feature is framed by "The newest version is determined collectively. The power to add new information is distributed across all participants (not centralized to the forest owner).". The last DLT feature "Transparent" is also left unchained and framed by "Information and its provider are visible for everyone, there is no access control. This includes new and past information.".

This framing enables the respondents to understand the advantage of a DLT with respect to the discussed implications for forest management. The self-explained judgments could be expressed in a pairwise comparisons for each of these four features' manifestations. For example, for the feature "Shared knowledge", the left manifestation is "The knowledge is central" while the right manifestation is "The knowledge is decentral". The scale between these two manifestations is "Absolute dominated", "Much more important", "More important" in both directions – the same holds for the other DLT features. Moreover, for each feature, the satisfaction of the current situation of the forest with respect to that feature is elicited by a four-point likert scale reaching from "Very little" to "Very much". The same likert scale is used for a further question (for each DLT feature) relating the willingness to spend own resources to get that feature realized. Especially the last question intends to associate individual costs with the provision of that feature.

The next "question group 4" includes two question. The first question is to weight the preferences for the three classic forest functions (Hanewinkel, 2011) in ascending order: Protective function, utility function, and recreational function. The most preferred function is assigned a 1 (most important), and the least preferred function is assigned a 3 (least important). The last question is meant to be a control question by which the knowledge of blockchain is elicited. By eliciting this information, possibly confounding elements might be discovered during the judgment phase for the DLT-oriented features. At this, the respondents self-explain in the five-point range of "not available" to "Expert" the given level of knowledge for the technology DLT.

The original questionnaire can be seen in Section A.2 in Figure A.1. The above-mentioned features are interconnected among themselves. Especially within the DLT-based features, a Multi-Criteria Decision Analysis (MCDA) is used in order to calculate the optimal DLT alternative. In combination with the preferred degree of participation impact, best DLT-alternatives can be recommended, respectively.

Operationalization of and Relations Between Features

The features used in the questionnaire are subject to specific manifestations and value ranges, and are interconnected among themselves. Since the analysis follows a MCDA, the analysis further includes part-worth utilities. Those part-worth utilities divide the overall utility down to utilities on the level of feature manifestations. The MCDA approach is especially used with respect to any DLT alternative, which is defined by the above-mentioned four describing features of DLT, and denoted with C_k for all $k = DE, CD, IM, TR$ (DE for "Decentralized", CD for "Consensus driven", IM for "Immutability", and TR for "Transparency".). Each of these criteria C_k has exactly two manifestations, i.e. the feature is enabled or disabled. For example, C_{DE} consists of *Knowledge is not shared* (disabled) versus *Knowledge is shared* (enabled). That way, the former one means the disabled manifestation while the latter one means the enabled manifestation – which is true for each DLT-feature (in a MCDA sense, features are known as criteria). Since there are no conflicts between the manifestations of the criteria, all resulting combinations are assumed to be possible and henceforth called alternatives. When each DLT-based criteria consists of two manifestations, it result 16 alternatives according to

$$|C_{DE}| \times |C_{CD}| \times |C_{IM}| \times |C_{IR}| = 2^4 = 16$$

which are also completely enumerated in Table 9.3.

DLT	Immutability	Consensus Driven	Transparency	Decentralization
1	Mutable	Concentrated Power	Intransparent	Centralized
2	Mutable	Concentrated Power	Transparent	Centralized
3	Mutable	Distributed Power	Intransparent	Centralized
4	Mutable	Distributed Power	Transparent	Centralized
5	Mutable	Concentrated Power	Intransparent	Decentralized
6	Mutable	Concentrated Power	Transparent	Decentralized
7	Mutable	Distributed Power	Intransparent	Decentralized
8	Mutable	Distributed Power	Transparent	Decentralized
9	Immutable	Concentrated Power	Intransparent	Centralized
10	Immutable	Concentrated Power	Transparent	Centralized
11	Immutable	Distributed Power	Intransparent	Centralized
12	Immutable	Distributed Power	Transparent	Centralized
13	Immutable	Concentrated Power	Intransparent	Decentralized
14	Immutable	Concentrated Power	Transparent	Decentralized
15	Immutable	Distributed Power	Intransparent	Decentralized
16	Immutable	Distributed Power	Transparent	Decentralized

TABLE 9.3: Theoretical DLT alternatives

In order to translate the self-explained weights of each respondent $i \in N$ over these alternatives, Equation 9.1 shows the associated part-worth utilities $\beta^i_{j,k}$ for each alternative $A_j \in A$ and each criteria $C_k \in C$ for each respondent i of the survey (contained by a utility matrix Y^i). The part-worth utilities express the importance of the manifestation of the criteria from the respondent's viewpoint, that is $\beta^i_{j,k} \in [0, 1]$, where $\beta^i_{j,k}$ is calculated by the weight respondent i gives to the importance of the manifestation of the criteria k for alternative j. Put differently, each respondent judges the importance of the manifestations of criteria k by pairwise comparison between the enabled and the disabled one. In addition to the scale introduced above, the numeric scale is from "Absolute dominated" (weight 4), "Much more important" (weight 3), "More important" (weight 2) in both directions. While doing this, the respondent is asked to put only one weight, since the corresponding other weight is automatically derived by division (as known from Pairwise Comparison (PC) of Saaty (2002)). Following this, the weight for one manifestation of criterion k is in the list $(\frac{1}{4}, \frac{2}{3}, \frac{1}{2}, 2, 3, 4)$. Due to reciprocity, the other weight is automatically derived by dividing by 1. After this, both values are normalized to sum up to 1 and are represented by $\beta^i_{j,k}$. This basically means that the most preferred alternative sums up to 4 because there are four criteria given and each manifestation can reach 1 at best.

$$Y^i = \begin{array}{c} \\ A_1 \\ \vdots \\ A_j \\ \vdots \\ A_m \end{array} \begin{array}{c} \begin{array}{ccccc} C_1 & \cdots & C_k & \cdots & C_o \end{array} \\ \begin{pmatrix} \beta^i_{1,1} & \cdots & \beta^i_{1,k} & \cdots & \beta^i_{1,o} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \beta^i_{j,1} & \cdots & \beta^i_{j,k} & \cdots & \beta^i_{j,o} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \beta^i_{m,1} & \cdots & \beta^i_{m,k} & \cdots & \beta^i_{m,o} \end{pmatrix} \end{array} \tag{9.1}$$

Similar to a classic MCDA, part-worth utilities on the level of alternatives are derived. Since the questionnaire does not contain the complete enumeration of all alternatives due to space restrictions as shown in Table 9.3, the part-worth utilities are elicited by self-explained weights directly in the form of part-worth utilities on the level of manifestations. The resulting part-worth utilities can then be used for each alternative consisting of this manifestation.

With this structure in mind, it is possible to generate the overall utility for each respondent i. The most preferred alternative of respondent i can be then found by summarizing the part-worth utilities $\beta^i_{j,k}$ for all manifestations of criteria C_k within any alternative A_j. With respect to the Equation 9.1, that means to sum up row-wise and to sort then in descending order on the basis of that sum – resulting in the most preferred alternative with its highest utility on top, which is depicted with

$$A^i_* = \underset{A_k \in A}{\arg\max} \sum_{C_j \in C} \beta^i_{j,k}$$

for respondent i. In order to aggregate across multiple respondents $i = 1, \ldots, n$, the part-worth utilities and overall utilities can also be summarized.

On the basis of the part-worth utilities Y^i of each respondent i, each Y^i has 16 entries – one per DLT alternative. While each respondent i has judgments for the 16 alternatives, each respondent i has further five participation impacts "Inform", "Consult", "Involve", "Collaborate", and "Empower" judged. Hereafter, the participation impact feature is denoted with $P = (INF, CON, INV, COL, EMP)$, while the part-worth utilities for these manifestations are denoted with β^i_p for $p \in P$. Once both β^i_p for $p \in P$ and Y^i are combined together, it can then for each respondent be derived which DLT alternative is preferred for which participation impact of P.

9.3 Data Insights

The survey took place in the period of the 29th November 2019 until 15th June 2020. In this period, 102 respondents with completed answers were able to get recruited in both a physical – by face-to-face – way (13 respondents) [6] and an online survey (89 respondents). From all respondents together, 56 were female and 46 were male. The averaged males' birthday is 1984 (min 1954, max 1998) with a variance of 222.56. The averaged females' birthday is 1986 (min 1954, max 2001) with a variance of 174.51. With respect to the highest educational degree, two respondents explained to have a apprenticeship, 29 explained to have high school, 4 explained to have a Ph.d, and 5 explained to have a secondary school degree.

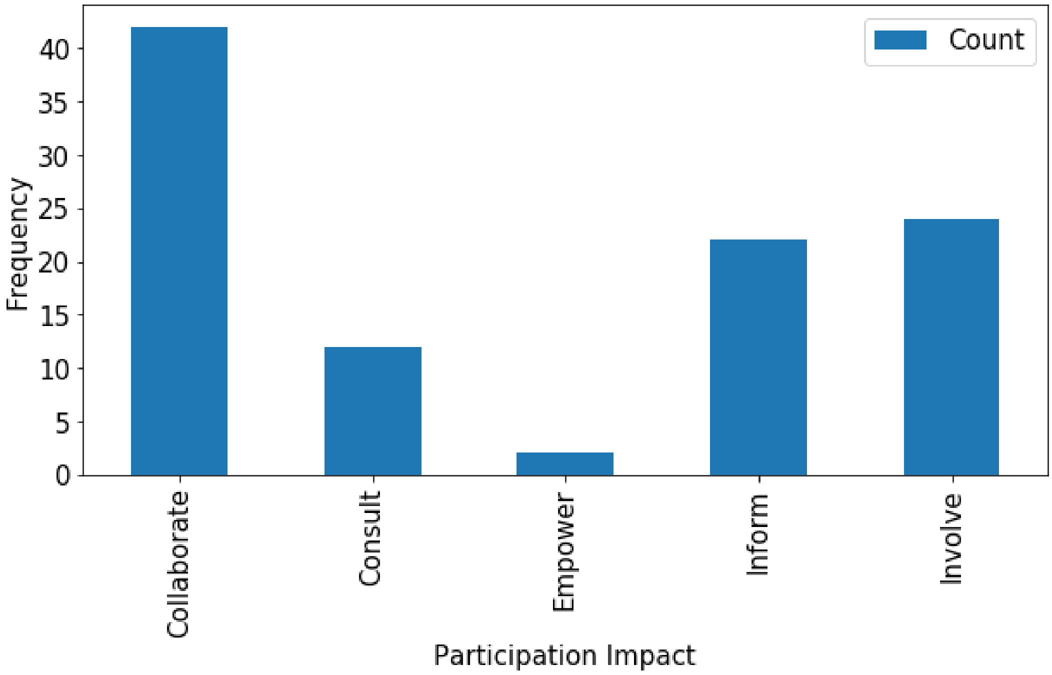

FIGURE 9.1: Frequency of the most preferred participation impact level

The first insight is given by the most preferred participation impact level across all respondents in Figure 9.1. As the figure shows, *collaborate* is the most preferred level of preferred participation with > 40, followed by involve, inform, consult, and empower < 5. A bit more detail is provided by Table 9.4, which is strongly related to both the participation impacts and the DLT alternatives listed in Table 9.3. This table gives insights into the relative count of the most preferred DLT alternatives for each respondent with respect to every participation impact level. Each cell shows the relative count of how many respondents have said the corresponding alternative and the corresponding participation impact level to be most preferred. At this, the rows in Table 9.4 are sorted in descending order by the last column *Sum*, such that the most preferred alternative is on top. The sum over all row and participation impact levels is 1, while the column *Sum* shows the row-wise sum for the specific alternative.

[6] On the Bits & Báume Conference in Eberswalde, Germany, on the 29th November 2019

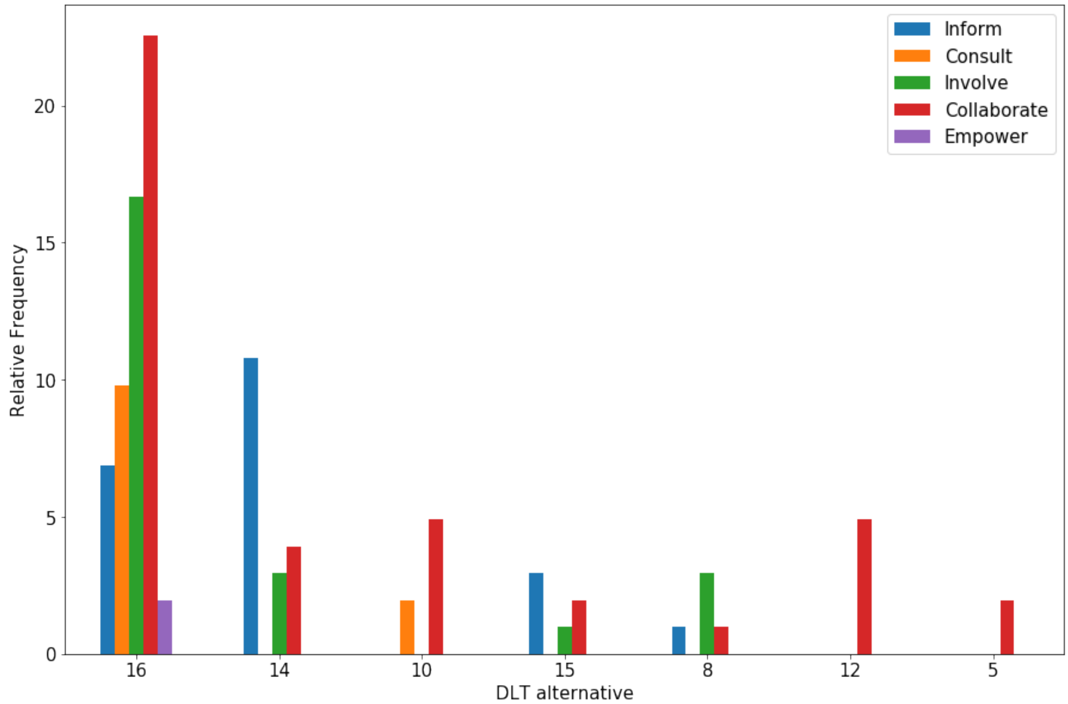

FIGURE 9.2: Diagram showing the most preferred DLT alternatives for different participation impact levels

As shown, DLT 16 is most preferred by – relatively – 57.84 respondents, while – within this row – *collaborate* with 22.55 is preferred over other levels of the participation impact, followed by *involve* with 16.67, *consult* with 9.80, by *inform* with 6.86, and *empower* with 1.96. The DLT itself is characterized by immutability, distributed power, transparency, and decentralization.. The DLT 14 is second-most preferred, and is characterized in the same way as DLT alternative 16, except for the criterion *Consensus Driven* with *Concentrated power* instead of *Distributed power*. Moreover, the table supports the conclusion that DLT 14 is mostly preferred by respondents who prefer *inform* as participation impact with a relative count at 10.78. As can be seen that the table lists not all DLT alternatives mentioned in Table 9.3 – the reason for that is that the non-mentioned alternatives are never preferred at first.

DLT	Inform	Consult	Involve	Collaborate	Empower	Sum
16	6.86	9.80	16.67	22.55	1.96	57.84
14	10.78	0.00	2.94	3.92	0.00	17.64
10	0.00	1.96	0.00	4.90	0.00	6.86
15	2.94	0.00	0.98	1.96	0.00	5.88
8	0.98	0.00	2.94	0.98	0.00	4.90
12	0.00	0.00	0.00	4.90	0.00	4.90
5	0.00	0.00	0.00	1.96	0.00	1.96

TABLE 9.4: Frequency of most preferred DLT alternatives

A more detailed insight is given with Table 9.5. The values mentioned in the

DLT	Inform	Consult	Involve	Collaborate	Empower	Sum
16	1.84	1.85	1.85	1.87	1.81	9.22
14	1.66	1.67	1.67	1.70	1.63	8.33
12	1.53	1.54	1.54	1.57	1.50	7.68
15	1.49	1.50	1.51	1.53	1.46	7.49
8	1.48	1.50	1.50	1.52	1.45	7.45
10	1.35	1.36	1.37	1.39	1.32	6.79
13	1.31	1.32	1.33	1.35	1.28	6.59
6	1.31	1.32	1.32	1.34	1.27	6.56
11	1.18	1.19	1.20	1.22	1.15	5.94
4	1.18	1.19	1.19	1.21	1.14	5.91
7	1.14	1.15	1.15	1.17	1.11	5.72
9	1.00	1.01	1.02	1.04	0.97	5.04
2	1.00	1.01	1.01	1.03	0.96	5.01
5	0.96	0.97	0.97	1.00	0.93	4.83
3	0.83	0.84	0.84	0.87	0.80	4.18
1	0.65	0.66	0.67	0.69	0.62	3.29

TABLE 9.5: Relative importances of DLT alternatives for all participation impacts

cells are calculated on the basis of Subsection 9.2. That is, all part-worth utilities $\beta^i_{j,k}$ of all respondents $i = 1, \dots, n$ for each alternative $A_j \in A$ and each criteria $C_k \in C$ are considered – together with their utilities for the five participation impact levels. According to this, each respondent i has $5 \times 16 = 80$ different utilities. With these utilities in mind, each cell represents the relative sum over the utilities of all respondents for that DLT alternative and that participation impact level; that way, the sum of all values of these cells sum up to 100, while the last column sums up row-rise. Consequently and consistent to Table 9.4, alternative 16 yields highest utility, especially for *collaborate* with a relative utility sum of 1.87, followed by 1.85 for both *consult* and *involve*, by 1.84 for *inform*, and 1.81 for *empower*.

Table 9.6 shows the preferences of the respondents across the different forest functions productive function, protective function, and recreational function. The column *weight* represents the relative sum weight over the normalized weights for the judgments of the respondents to the forest functions' manifestations. The last columns *Count of Rank 1, 2, 3* refer to the relative occurrence of the corresponding forest function with the specified rank. Thus, the *productive function* was never ranked on 1, but oftentimes on rank 3. It can roughly be derived that the protective function is most often ranked to 1 and that it changes its counts with the recreational function with regard to rank 2 occurrences.

With Table 9.7, the relations between the forest functions for the different levels of participation impacts are given. The values reply how many respondents prefer the mentioned levels of participation impact, depending on the forest function they prefer at most. As already revealed by Table 9.6, the productive function was

Forest Function	Rel. Weight	Count of Rank		
		1	2	3
Productive Function	0.19	0.00	0.06	0.28
Protective Function	0.47	0.27	0.06	0.00
Recreational Function	0.34	0.06	0.22	0.06

TABLE 9.6: Forest function preferences

never preferred with rank 1. As indicated by 9.6, the protective function was mainly preferred, followed by the recreational function. Most of the respondents prefer the participation impact level *collaborate*, followed by *involve*, *inform*, and *consult*. The level *empower* was also never preferred at rank 1 of those who prefer protective function at rank 1.

Participation Impact	Forest Function		
	Productive	Protective	Recreational
Inform	0	19	3
Consult	0	8	4
Involve	0	24	0
Collaborate	0	32	10
Empower	0	0	2

TABLE 9.7: Relations between forest functions and participation impact levels

9.4 Conclusion

A Participatory Decision-Making System (PDMS), which is based on the value-adding features of a DLT, could promise to enhance the process along participation for common goods, more precisely on the forestry. The value-adding DLT features might increase the acceptance of decisions with respect to common goods, e.g. the forestry. This work can give first valuable insights on the degree of value-adding support several such DLT-specific features might give. In line with this, this work was driven by the research question of how much value a PDMS can give to whom, and was answered by a questionnaire distributed in physical (face-to-face) and online channels. Altogether, 102 respondents reply with completed questionnaires. The analysis of the results follows a combination of features of a CA and MCDA, since the DLT features are modeled in a multi-criteria sense and both these DLT features and the different levels of participation impact are analysed by part-worth utilities. At the end, different DLT alternatives give different utilities, while different levels of participation impacts are differently preferred, such that these alternatives varying in satisfying these needs.

This work showed that the level *collaborate* of participation impact is strongest preferred, while a transparent, immutable, with a decentralized power, and a decentralized DLT is mostly favored. However, an alternative having centralized power instead of decentralized power is preferred by those who strongly prefer to get informed about activities around the forest. Moreover, the protective function is over the recreational function preferred, while the productive function was never preferred at most. As shown, those preferring the protective function are also interested in collaborating and involvement, which leads to the conclusion that, for this sample, people whose preferences are mostly consistent with the protective function benefit at most when using a DLT being transparent, immutable, with a decentralized power, and with a decentralized structure.

The presented work is subject to some limitations and provides opportunities for further research. First of all, the elicited sample can just allow a first insight to the question which DLT alternative is preferred by whom and to what extent utility can be given. Since the mentioned DLT features are not embedded in a technical sense, the respondent might not be able to understand its complexity and might not be able to look at the underlying technology in its entirety. Some side effects or emergent properties (such as technology propensity or usability aspects) are not considered, and restrict the external validity of this study. Nevertheless, the respondents valued the DLT-specific features and self-explained that these features might add value with respect to the forestry participation.

Chapter 10

A Reduced Design of Pairwise Comparison (PC) in Analytic Hierarchy Process (AHP) – an Experimental Analysis

> It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiment, it's wrong.
>
> Richard P. Feynman

10.1 Introduction

Multi-Criteria Decision Analysis (MCDA) is a powerful discipline in decision-making (see Thokala et al., 2016; Steele et al., 2009, for decision-making in health care decision-making and the environmental decision-making fields). Generally, MCDA can be understood as a sub-discipline of operations research. MCDA helps decision makers in deciding thoroughly, especially in complex decision-making situations. Such methodologies take complex problem statements with explicitly conflicting multiple-criteria into account and recommend solutions, that are usually based on a systematic solving approach. There are plenty special methods present decision makers might recourse to (see Zardari et al., 2015b; Goldstine, Kintala, and Wotschke, 1990; Papathanasiou and Ploskas, 2018, for a well-elaborated overview). A powerful MCDA method for deciding in a systematic way is given by the Analytic Hierarchy Process (AHP) by Saaty (1980) (and Velasquez and Hester (2013b) and Saaty and Vargas (2012)), whose popularity is quite high (Ishizaka and Labib, 2011).

The AHP undertakes judgments by means of Pairwise Comparison (PC) (Saaty, 1980; Saaty, 2002) to express preferences, i.e., to elicit relative importances between criteria (or attributes). Further, among decision makers, PC obtains no high acceptance (Zardari et al., 2015b). This might be caused through a huge amount of sub--decisions required until all pairs of PC are judged. Basically, expressing preferences keeps a challenge (see Toubia et al., 2013; Aggarwal and Vaidyanathan, 2003; Merino-Castello, 2003). Respondents might cause deviations between the given preference and the true preference for some reasons. Of course, it might be a result of strategic reflections to misreport preferences. But it could also be a simple misrepresentation of true preferences. This misrepresentation might be due to the fact that a complicated methodology was used to quantify preferences (e.g. at the Analytic Hierarchy Process (AHP), see Kwiesielewicz and Van Uden, 2004). Respondents are sometimes facing uncertainties in preference elicitation and might therefore sometimes only be able to express preferences in a fuzzy way (Kahraman, Cebeci, and Ulukan, 2003).

According to a full design of PC, there are $0.5 * o * (o - -1)$ sub-decisions required where o depicts the number of given criteria in a problem statement. This causes some disadvantages relating the full design of PC, e.g., (1) inconsistencies between PC judgments (Kwiesielewicz and Van Uden, 2004) and (2) the fast-growing number of comparisons (due to $0.5 * o * (o - 1)$) and (3) hence the time-consuming judgment effort for decision makers, which might result in a PC cognitive challenge.

Instead of using a full design for PC, it might also be possible to use a reduced design of PC. In this experiment, the reduced design of PC is based on the work of Koczkodaj and Szybowski (2015b) with a strongly reduced number of comparisons required, i.e., just $o - 1$ comparisons are required while the others are autocompleted. Consequently, inconsistencies (1) are not possible (by design) and the fast-growing number of comparisons is avoided (2, 3). This advantages given, it keeps an open question whether this kind of elicitation of preferences will lead to the same quality compared to the full design. This question is broken down to two main research questions examined in an online experiment.

10.2 Related Work

This work is about the PC in AHP and and is positioned in the filed of information system, decision theory, and marketing. First, PC can be understood as weighting method. In literature, different weighting methods have been proposed to assign weights to criteria (Pöyhönen and Hämäläinen, 2001; Belton and Stewart, 2010). Zardari et al. (2015a) published a list of most used subjective weighting methods, namely direct rating, ranking method, point allocation, PC, ratio method, swing method, graphical weighting, Delphi method, SMART, SIMOS method (in this order). Further, Zardari et al. (2015a) provided an overview about the acceptance of different weighing methods and concluded that PC is perceived to be *best* as often as ranking and is only dominated by fixed point. Anyway, these results also show that the majority of respondents had judged PC to be the worst one, which motivates research to mitigate that drawback. Especially the latter one might be due to the fact that PC is a hard task when the number of criteria to be judged is large, inconsistencies might be in the resulting preference, and the conduction is usually only possibly in a computer-aided environment.

Toloie-Eshlaghy and Homayonfar (2011) state that assigning weights to criteria in a MCDA is the most difficult task. However, each weighting method differs in terms of accuracy, ease of use, complexity for users, and theoretical foundations, and produces therefore different sets of criteria weights (Zardari et al., 2015a). Following this, several comparative studies suggest that no dominant preference measurement approach exists (Louviere and Woodworth, 1983; Natter and Feurstein, 2002; Kamakura and Ozer, 2000). For conducting MCDA, several methods were published. Papathanasiou and Ploskas (2018) lists TOPSIS, VIKOR, PROMETHEE, SIR, AHP, and Goal Programming, but mentioned that this list is not exhaustive and other interesting methods exist as well. Among these, AHP is known to be a widely used methodology for both practitioners and academics (Ishizaka and Nemery, 2013). Since the AHP uses PC by design, the afore-mentioned drawbacks need to be considered. So far, AHP was criticized by several researchers and many modifications had been proposed, focussing on ratio scales or methods to build the priority vector. To face with uncertainty, several combinations with fuzzy logic (Buckley and Uppuluri, 1987; Chang, 1996; Golany and Kress, 1993) and group decision-making (Van Laarhoven and Pedrycz, 1983; Dong et al., 2010; Saaty, 1989) were made (Papathanasiou and Ploskas, 2018). Besides this and as outlined by Vaidya and Kumar (2006b), AHP was most used in the area engineering, personal, social, manufacturing, industry, government, education, political, and others (in this order).

The problem of the large number of pairwise comparisons required to conduct AHP completely is known and an area of research. Therefore, some studies examine incomplete PC matrices, i.e., some studies explore the possibility of reconstruct the entire PC matrix when an incomplete matrix is given. Harker (1987) examined how to deal with incomplete decision matrices when they occur. For example, Carmone Jr, Kara, and Zanakis (1997) had used a completion algorithm to complete the incomplete matrix (but there, the accuracy is reduced with a reduced number of given values in the matrix).

10.3 Research Outline

The first aim of this experiment is to compare the accuracy rate of the full design versus the reduced design of PC, where the reduced design is depicted as PC_r and the full design is depicted as PC_f. A further separation is made to examine the effect of the visualization of the criteria weights during the criteria judgment phase. A visual representation in terms of a diagram helps decision makers to understand the criteria weights more intuitively – instead of requiring the decision maker to be able to oversee the order with different distances between the criteria entirely and permanently during the judgment phase. Diagrams are able to impart numbers in a more understandable way, such that humans are more efficiently be able to grasp the numbers (Larkin and Simon, 1987).Because PC (in the full design) requires multiple comparisons, which grow exponentially when the number of criteria increases, contradictions might result between the judgments. Especially with a particular degree of uncertainty, the decision maker might judge inconsistently. For these reasons, this work examines a bar diagram as a first diagram (to the best knowledge of the author, it has been never before examined the effect of a bar diagram in this context) to visualize the criteria weights. Once the treatment with a bar diagram is involved, this is depicted as D_+, and D_- otherwise. The performance of a group is mainly measured by the accuracy rate of the PC. The accuracy rate, in turn, is operationalized to the FCHR (abbreviated with FCHR), which is introduced in Section 10.4.2.

The respondent uses PC to reach criteria weights where utilities of alternatives are derived from. After choosing preferred alternatives by a respondent, the FCHR reveals how well the PC was able to predict the choices. This is examined by four groups, i.e. $\text{PC}_f D_-$ as baseline, and $\text{PC}_f D_+$, $\text{PC}_r D_-$, $\text{PC}_r D_+$ as treatments. Furthermore, the experiment contains a Conjoint Analysis (CA) to benchmark the performance of the PC against a well-established methodology in marketing to quantify preferences.

Operationalization of the Research Questions

Overall, there are two research questions. The first research question (6) is about the difference of the accuracy rate regarding the reduced design of PC by Koczkodaj and Szybowski (2015b) in comparison to the full design, which is usually used when conducting the AHP. The second research question is about the usage of a bar diagram in order to display the criteria weights during the judgment phase. The following explanatory notes operationalize these research questions step-by-step.

Research Question 6

Research question 6 is *The reduced design of the Pairwise Comparison (PC) by Koczkodaj and Szybowski (2015b) integrated in the Analytic Hierarchy Process (AHP): Is it better or equal to the full design?* and is operationalized as follows:

The endogenous variable to answer this question is the accuracy rate of the PC embedded in the AHP in relation to the real choices of the respondents made in a CE. The AHP is used to associate each alternative with a unique utility according to the preferences elicited by the PC, either by the full PC_f or reduced PC_r design, with D_+ or without D_- bar diagram. This utility depends mainly on the PC and depends on each respondent. As outlined in Section 10.4.2, and especially in Equation 10.4, the accuracy rate is measured by the variable $FCHR^i \in \mathbb{R}, 0 \leq FCHR^i \leq 1$, which is the averaged FCHR of a respondent $i \in N$ where N is a set of respondents in the experiment. While the endogenous variable is given with $FCHR^i$ for respondent i, the exogenous variable being in focus is binary-scaled and expresses the group of the respondent i, that is PC_f (as baseline) or PC_r (as treatment) (for further information, see Table 10.3).

This research question is driven by the hypothesis that the reduced design PC_r yields another accuracy rate with respect to $FCHR^i$ comparing to the full design PC_f.

- Null hypothesis $H_{6_0} : \mu_{FCHR^{\text{PC}_f}} = \mu_{FCHR^{\text{PC}_r}}$
- Alternative hypothesis $H_{6_1} : \mu_{FCHR^{\text{PC}_f}} \neq \mu_{FCHR^{\text{PC}_r}}$

The hypothesis consists of $\mu_{FCHR^{\text{PC}_f}}$ and $\mu_{FCHR^{\text{PC}_r}}$, representing the population mean of the respective samples, that is PC_f and PC_r. The hypothesis H_0 asserts that no difference is between PC_f and PC_r. The alternative hypothesis H_1 asserts that there is a difference between PC_f and PC_r that might be positive or negative, i.e., the reduced design might perform better or worse in comparison to the full design.

This research question is accompanied by the next two explained hypotheses. The first hypothesized that the reduced design of PC changes the cognitive load during the judgment phase and is operationalized as follows:

The endogenous variables to examine this hypothesis consist of the questionnaire NASA TASK LOAD INDEX (TLX), measuring the overall workload of a respondent i. The workload is measured by six questions in total, which are presented in the appendix, see Section A.1.1. Each question is then normalized to be in the range of $[-50, +50]$ (boundaries included), while the higher the values are, the more they are associated with a higher effort or (work-)load. In contrast, the lower the value, the more the respondents have experienced a lower effort or (work-)load during the PC task, being either $\text{PC}_f D_-$, $\text{PC}_f D_+$, $\text{PC}_r D_-$, or $\text{PC}_r D_+$. The hypothesis is therefore that the reduced design PC_r yields another effort or (work-)load in comparison to the full design PC_f.

- Null hypothesis $H_{6.1.k_{(a,b)_0}} : \mu_{\text{TLX}_{k_b}} = \mu_{\text{TLX}_{k_a}}$
- Alternative hypothesis $H_{6.1.k_{(a,b)_1}} : \mu_{\text{TLX}_{k_b}} \neq \mu_{\text{TLX}_{k_a}}$

For both hypotheses, the index k refers to the several six questions of the TLX questionnaire $k = 1, \ldots, 6$. The other two indices a, b refer to the groups the hypothesis are valid for. That is $groups = \{(a_{i,j}, b_{k,l}) : (i \geq k \wedge j \geq l) \wedge (i \neq k \wedge j \neq l) \wedge \neg(i \leq k \vee j \leq l)\ \forall\ i,k = \ldots, |PC|,\ \forall\ j,l = 1, \ldots, |D|\}$, where $PC \in \{\text{PC}_f, \text{PC}_r\}$ and $D \in \{D_-, D_+\}$. The groups are chosen in such a way that each treatment is compared with each baseline and no comparison consists of more than one treatment to be able to determine the effect clearly. This procedure results in the groups to be compared as shown in Table 10.1. The group comparisons depicted in Table 10.1, together with the questions of the questionnaire TLX, there result $6 \times 4 = 20$ hypotheses.

Baseline (a)	Treatment (b)
$PC_f D_-$	$PC_r D_-$
$PC_f D_+$	$PC_r D_+$
$PC_f D_-$	$PC_f D_+$
$PC_r D_-$	$PC_r D_+$

TABLE 10.1: Groups to be compared

The second hypothesis focuses on a classic CA. It is hypothesized that the reduced design of PC leads to different results compared to classic CA and is operationalized as follows:

The CA is used as benchmark to estimate the accuracy rate of the PC in the reduced design PC_r in relation to the full design PC_f. It is therefore assumed that the CA performs well in both groups PC_f and PC_r, and will at least produce the same results in a steady manner. While doing so, the CA is known as a powerful method in marketing to elicit and quantify preferences. To examine the accuracy rate, the criteria weights can be used for both approaches, the CA and the PC. The derived preferences by means of the CA are then used to estimate the utilities of the alternatives shown in the CE. Consequently, the FCHR can be used again.

- Null hypothesis $H_{6.3.1_0} : \mu_{FCHR_{\text{PC}_r}} = \mu_{FCHR_{\text{CA}}}$
- Alternative hypothesis $H_{6.3.1_1} : \mu_{FCHR_{\text{PC}_r}} \neq \mu_{FCHR_{\text{CA}}}$

Following this null hypothesis, it is assumed that no difference between the CA and the PC_r relating the FCHR exists. The alternative hypothesis asserts then that a difference is existing, that is that the CA yields another FCHR than PC_r. While asserting this difference, the CA can be understood as an established method to quantify preferences in marketing and therefore used to benchmark against. To further examine on the level of criteria weights, criteria weights can be derived by means of the CA. The criteria weights can then be compared with the criteria weights of the PC. This examination is driven by the following hypotheses.

- Null hypothesis: $H_{6.3.2_0} : \mu_{r_{\text{PC}_f,\text{CA}}} = \mu_{r_{\text{PC}_r,\text{CA}}}$
- Alternative hypothesis: $H_{6.3.2_1} : \mu_{r_{\text{PC}_f,\text{CA}}} \neq \mu_{r_{\text{PC}_r,\text{CA}}}$

The variable $r_{\text{PC}_f,\text{CA}}$ represents the Pearson correlation coefficient between criteria weights of PC_f and CA. In an analogous manner, the Pearson correlation coefficient $r_{\text{PC}_f,\text{CA}}$ measures the correlation between the criteria weights of PC_f and CA.

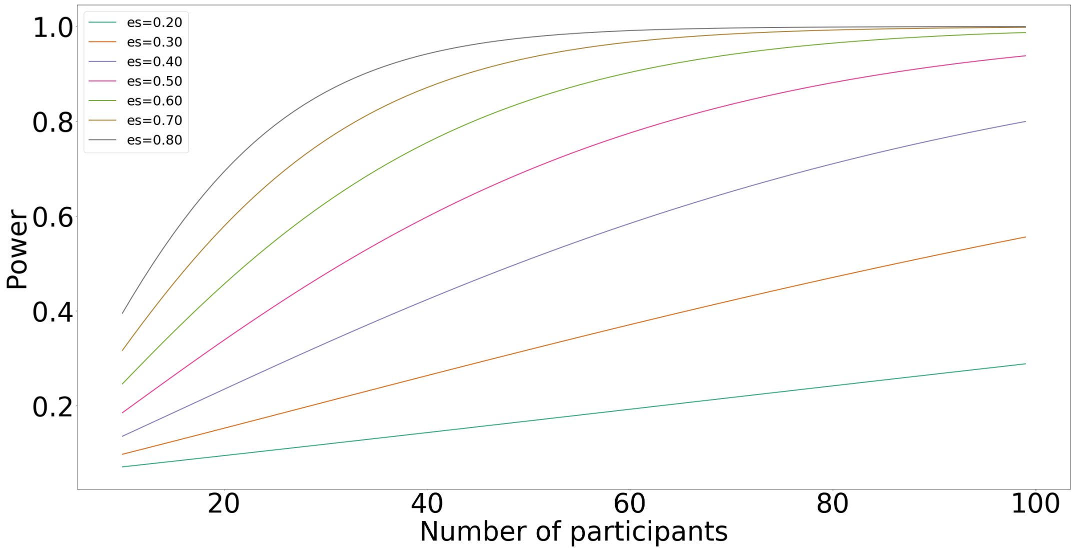

FIGURE 10.1: Power analysis over an increasing number of participants (the lines show the effect size (es))

The corresponding power analysis was conducted with respect to the first research question and is shown in Figure 10.1. This analysis shows for an effect size of 0.4 and a power of 0.8, around 100 (99.080 exactly) respondents are needed to be recruited. For an effect of 0.2 and around 100 respondents, the power is reduced to 0.291, i.e., the β failure (false positive) would be at 0.709. To accept this research hypothesis, an effect size of 0.4 with a power of 0.8 is used to reduce the probability of random results or the probability of false positives, resulting in invitations of around 100 respondents per group.

Research Question 7

Research question 7 is *Does a bar diagram affect the accuracy rate when displaying the relative importances of the criteria during the Pairwise Comparison (PC) phase?* and is operationalized as follows:

A bar diagram is intended to be used to support the PC weighting methodology. To do so, a special treatment is devoted. To indicate that a bar diagram is present, D_+ (treatment) is used, and D_- (baseline) otherwise. *Accuracy rate* means FCHR again already used in the main research question 6. Therefore, this research question is driven by the hypothesis that, if a bar diagram is present D_+, another accuracy rate is reached with respect to $FCHR^i$ compared with no bar diagram is present D_-.

- Null hypothesis $H_{6.2_0} : \mu_{FCHR_{D_-}} = \mu_{FCHR_{D_+}}$
- Alternative hypothesis $H_{6.2_1} : \mu_{FCHR_{D_-}} \neq \mu_{FCHR_{D_+}}$

As described before, $FCHR$ is is used to measure the accuracy rate of PC in the treatment. In difference to the above-stated hypothesis, here the presence of a bar diagram D_+ is examined. This is why the hypothesis contains the explicit denotation through the index D_- versus D_+. It is assumed that the presence of a bar diagram D_+ results in a difference of the PC accuracy rate.

10.4 Design of Experiment (DoE)

The Design of Experiment (DoE) contains information about structure of the experiment, in which ways the respondents walked through the experiments, the variables elicited, the realization of the steps of the experiment, and the use case the respondents have been faced with. The experiment is designed to consist of three treatments and a baseline (four groups) as shown in Figure 10.2. The black bold lines show that the content of these belong together, while the arrows left and right illustrates that this block is interchangeable to the CA.

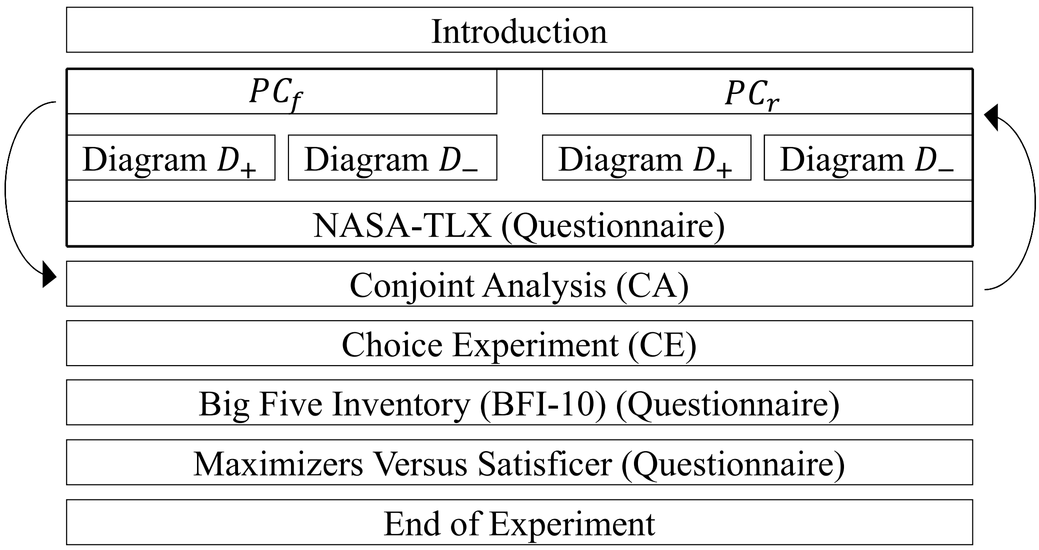

FIGURE 10.2: Process of the experiment

First, the experiment starts with an introduction where the use case is explained including the attributes and attribute levels the use case consists of, as outlined in Table 10.4. As part of the introduction, each respondent was asked to expose the demographics shown in Table 10.2. While age, gender, and education are well-established, whose eliciting is quite usual, the feature *Last apartment Search* is rather understood to be an additional control variable. The assumption is that respondents who are currently looking for an apartment, for example, might be more able to put oneself in the situation drawn by the use case of looking for a new apartment.

Afterwards, the respondents were randomly assigned to the groups. For convenience and as described above, the PC group with the full design is indicated with

Variable	Explanation
Age	The year of birth: 2010 - 1921
Gender	The type of gender: male, female, diverse
Education	The level of education: Magister, Diploma, State Examination, Master, Bachelor, High-School Diploma, Vocational Education, No Education
Last apartment Search	When the respondent last looked for an apartment. Also floating-point numbers were possible. When the respondents were never looking for an apartment, they could disable the question. When the respondents were currently looking for an apartment, they were asked to set a 0.

TABLE 10.2: Control variables (including demographics)

PC_f and the group of the reduced design with PC_r. The group with or without a bar diagram is indicated by D_+ or D_-, respectively. In addition, the respondents were assigned randomly to the sequence to walk either through the benchmark CA (the step CA is indicated by CA) or through the PC group task at first. An overview about the resulting eight sequences (including the group) is given in Table 10.3. Note that also abbreviations are introduced to refer to the corresponding sequence and group easily. For example, when first the full PC group (as PC_f) with a bar diagram (as D_+) showing the importances is shown, followed by the CA (as CA) as benchmark component, this sequence is referred to as $PC_f D_+ CA$. The randomized assignment to the sequence of showing either CA or PC with or without a bar diagram first, is to exclude possible confounding effects that might be caused by learning effects or decreasing attention during processing the steps.

#	Abbreviation	First	Second
1	$\text{PC}_f\ D_+$ CA	$\text{PC}_f \wedge D_+$	CA
2	$\text{PC}_r\ D_+$ CA	$\text{PC}_r \wedge D_+$	CA
3	$\text{PC}_f\ D_-$ CA	$\text{PC}_f \wedge D_-$	CA
4	$\text{PC}_r\ D_-$ CA	$\text{PC}_r \wedge D_-$	CA
5	CA $\text{PC}_f\ D_+$	CA	$\text{PC}_f \wedge D_+$
6	CA $\text{PC}_r\ D_+$	CA	$\text{PC}_r \wedge D_+$
7	CA $\text{PC}_f\ D_-$	CA	$\text{PC}_f \wedge D_-$
8	CA $\text{PC}_r\ D_-$	CA	$\text{PC}_r \wedge D_-$

TABLE 10.3: Sequences of the steps of the experiment (CA means Conjoint Analysis (CA), PC means Pairwise Comparison (PC), D means Diagram)

The experiment is designed to work with attributes and alternatives originating from Akaah (1991). The original naming has been reused and slightly adapted due to pre-test results and understanding problems of test respondents. The used attribute titles are shown in Table 10.4 where the in the experiment used title is mentioned above and – for the sake of completeness – the English translation is given below.

The column *max/min* indicates whether the attribute is to be maximized or to be minimized. For example, the attribute "Commuting time to university" is assumed to be an attribute that is preferred to be as small as possible by respondents. The attribute "Safety on / in the apartment", in turn, is assumed to be an attribute that is preferred to be as high as possible by respondents. The level of measurement of all attributes is ordinal and linguistic, shown in column *Attribute levels*. Again, the first occurrence shows the original used version in the experiment and the English translation is given in brackets below.

Each respondent was guided in the same way. The use case each respondent was working on was introduced with the following explanation: *Bitte versetzen Sie sich möglichst gut in die folgende Situation hinein: Sie sind als Student/in auf der Suche nach einer neuen Wohnung und sehen sich verschiedene Angebote an. Jedes Wohnungsangebot besteht aus sechs Eigenschaften, die bei jedem Angebot anders ausgeprägt sind. (Please put yourself in the following situation best possible: You are a student looking for a new apartment looking at various offers. Each apartment offer consists of six attributes, which are differently characterized for each offer.)*

Although the real sequence might differ due to the possible sequences outlined in Table 10.3, the explanations with respect to the respective steps follow the structure of Figure 10.2. According to Figure 10.2, the immediately following step is the PC task, which is described in Section 10.4.1 including the the full PC_f, the reduced PC_r design of PC, without a bar diagram D_- or with a bar diagram D_+. This baseline and the possible treatments are also explained in more detail in Section 10.4.1. As shown in Figure 10.2, once a respondent has finished the PC task, the *NASA TASK LOAD INDEX (TLX)* questionnaire follows. The questionnaire can be found in the appendix at Section A.1.1 where Table A.1 contains the questions that were asked in the experiment. The TLX is related to the PC task where it is hypothesized that the respondents experience differences in their cognitive load during this task, i.e., the reduced design of PC PC_r might lead to a lower or higher degree of cognitive load in contrast to the full design PC_f since the number of pairs required is reduced considerably. Further, it is hypothesized that a bar diagram D_+ might further decrease the cognitive load since a bar diagram is able to visualized the current state of preference weights and might help to dissolve possible inconsistencies among the judgements in PC_f.

The next step shown in 10.2 consists of a Conjoint Analysis (CA) (see Chapter II for more details) and is used as one of the most frequently used methods to elicit customer's preferences in a quantitative way. The PC is benchmarked against a CA. This benchmark reveals additional information about the performance of the PC since both yield to preferences on the level of criteria (within CA, the criteria is named attributes) (the afore-mentioned CE combined with the PC lead to evidence with respect to the FCHR, that is the fitness of the real choices of the CE of the respondent to the prediction made by PC). More detailed information can be found

Id	Attribute's Title	max/min	Attribute Levels
1	Pendeldauer bis zur Universität *(Commuting time to university)*	min	1. 10 Minuten *(10 minutes)* 2. 20 Minuten *(20 minutes)* 3. 30 Minuten *(30 minutes)*
2	Geräuschlevel an / in der Wohnung *(Noise level on / in the apartment)*	min	1. Geringer Geräuschpegel *(Low noise level)* 2. Durchschnittlicher Geräuschpegel *(Average noise level)* 3. Hoher Geräuschpegel *(High noise level)*
3	Sicherheit an / in der Wohnung *(Safety on / in the apartment)*	max	1. Hohe Sicherheit *(High security)* 2. Durchschnittliche Sicherheit *(Average security)* 3. Geringe Sicherheit *(Low security)*
4	Sauberkeit an / in der Wohnung *(Cleanliness on / in the apartment)*	max	1. Hohe Sauberkeit *(High cleanliness)* 2. Durchschnittliche Sauberkeit *(Average cleanliness)* 3. Geringe Sauberkeit *(Low cleanliness)*
5	Größe des Wohn-/Essraums der Wohnung *(Size of the living / dining room of the apartment)*	max	1. 63 qm 2. 35 qm 3. 20 qm
6	Monatliche Miete (inkl. Nebenkosten) *(Monthly rent (incl. service charges))*	min	1. 315 Euro 2. 405 Euro 3. 540 Euro

TABLE 10.4: Attributes used in the experiment (reused and slightly adapted from Akaah (1991))

in Section 10.4.3 where the used methodology is explained and the (mathematical) integration in this experiment is shown.

At this point, all respondents have completed the different sequences of Table 10.3 and, henceforward, the further progress keeps equal for each respondent. Therefore, the next step, also shown in Table 10.2, is to ask each respondent for one choice with respect to four apartment alternatives (offers). This step is called Choice Experiment (CE) and takes place four times for each respondent. At the end, a respondent faced 4×4 different and randomized generated alternatives and chose 4 alternatives, exactly one in each of these four CE. The CE can be understood as a reference point to the PC and is explained in more detail in Section 10.4.2.

The last two steps shown in Figure 10.2 are questionnaires. The first questionnaire is related to the questionnaire Big Five-Inventory (BFI), where a short version is used (see Table A.3 for the questions asked) as described in Section A.1.2. This questionnaire is mainly used to discover unintended effects caused by personality and to introduce some more control variables. Later on, it can then be argued to recommend a reduced design, a full design, a bar chart to be displayed or not – depending on the personality (as known as adaptive system). The last questionnaire is Preference for Consistency Scale (PCS) that is described in Section A.1.3. Since this questionnaire is able to elicit the preference for consistency for all respondents, quantitative evidence is possible with respect to their behavior in the experiment, especially the PC task. In this context it is hypothesized that someone might have a higher correlation between, for instance, the PC, the CA, and the CE task, since someone has a high score in preference for consistency.

10.4.1 Baseline and Treatments

As shown in Figure 10.2, the experiment consists of four groups, i.e., the PC full (PC_f) as baseline versus the PC reduced (PC_r) as treatment, and each of them with a bar diagram (D_-) or without (D_+). In the following, the groups' meanings are explained, the structure of those and what variables are elicited.

Pairwise Comparison (PC) Full and Reduced

Considering Figure 10.2, the respondents might walk at first through the PC step (see Section 10.4.1) while the real order might differ since the sequences are assigned in a randomized way and are individual for each respondent (nevertheless, for explanation purposes, the sequences is explained in a top-down manner as shown in Figure 10.2). The full design (PC_f) is understood as baseline because it represents the conventional way of elicitation by PC (Saaty, 1980). The reduced design (PC_r) represents the group with the PC approach by Koczkodaj and Szybowski (2015b). Both approaches work with the original Saaty's scale shown in Table 3.1. Further, both approaches yield, at the end, a complete PC matrix and therefore there can a priority vector p^i for respondent $i \in N$ (with N as the set of participating respondents) be derived that contains relative importances among the criteria shown in Table 10.4. Based on the introduced notation of Equation 3.9, the function $PCV : C \rightarrow p$ is used as a abbreviation to refer to the priority vector that is reached by the judged criteria $C_k \in C$ where a complete PC matrix is assumed. Let PCV_f (PCV_r) indicate that the priority vector p^i is reached by the baseline group PC_f (by the group PC_r). The priority vector follows the structure

$$PCV^i(C) = p^i = (p^i_1, \ldots, p^i_k, \ldots, p^i_o)$$

for $k = 1, \ldots, o$, where o is the number of criteria given, i.e $o = |C|$, of respondent i.

Furthermore, because there are $o = 6$ criteria given in Table 10.4 and each of these criteria has exactly three manifestations, there are $3^6 = 729$ alternatives existing. One alternative is understood as the combination of manifestations of each criteria of Table 10.4. To formalize this, let X be the set of all alternatives such that $|X| = 729$ and $X = C_1 \times \cdots \times C_j \times \cdots \times C_o$. Let the corresponding matrix

$$X = (x_{j,k})_{m \times o} = \begin{array}{c} \\ A_1 \\ \vdots \\ A_j \\ \vdots \\ A_m \end{array} \begin{array}{c} \begin{array}{ccccc} C_1 & \cdots & C_k & \cdots & C_o \end{array} \\ \begin{pmatrix} x_{1,1} & \cdots & x_{1,k} & \cdots & x_{1,o} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ x_{j,1} & \cdots & x_{j,k} & \cdots & x_{j,o} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ x_{m,1} & \cdots & x_{m,k} & \cdots & x_{m,o} \end{pmatrix} \end{array}$$

be given that contains all alternatives and criteria manifestations within a matrix (as already introduced in Equation 3.1 with more explanatory details). Each element $x_{j,k}$ is assumed to be normalized among criteria, i.e., $\sum_{j=1,\ldots,m} x_{j,k} = 1$ for each $k = 1, \ldots, o$. For each respondent i, the part-worth utility can then be computed by

$$\beta^i_{j,k} = p^i_k * x_{j,k}$$

for the manifestation of criterion $C_k \in C$ at alternative $A_j \in A$ and the respondent's priority vector p^i . Following these part-worth utilities $\beta^i_{j,k}$, the total utility of an alternative $A_j \in A$ can be aggregated by

$$y^i_j = \sum_{k=1,\ldots,m} \beta^i_{j,k}$$

which is the relative utility among all alternatives $\sum_{j=1,\ldots,m} y^i_j = 1$. Finally, the alternative with the highest utility is determined $\max_{j=1,\ldots,m} y^i_j$ and assumed the best-suited alternative for respondent i. Once the PC results in respondent's i preference over the decision criteria C, the of i's most preferred alternative can be determined by AHP as described by Saaty (1980). Based on this aggregation in terms of Saaty (1980), the relative utility y^i_j for an alternative j of respondent i can be, on the one hand, achieved by PC_f or, on the other hand, by PC_r, depending on the group respondent i was assigned to. That way, both approaches lead to an *estimator* estimating the most preferred alternative j for respondent i.

Pairwise Comparison full

The PC full step is meant to be the baseline and is abbreviated by PC_f and means the conventional way to do PC embedded in the Analytic Hierarchy Process (Saaty, 1980; Saaty, 2002). As outlined by Part II, especially Chapter 3, the full PC requires

$$\frac{(o-1)*o}{2}$$

comparisons, is reached by constructing a PC matrix, and might be inconsistent, see Section 3.1.3.

In this baseline, each respondent has judged the same list of pairs of attributes in a randomized order. Based on the notation given in Chapter 3, an example all pairs of attributes are given in Equation 10.1. There might also be another order and other pairs, but the total number of pairs remains equally.

$$\begin{gathered}((1,2),(1,3),(1,4),(1,5),(1,6),\\ (2,3),(2,4),(2,5),(2,6),(3,4),\\ (3,5),(3,6),(4,5),(4,6),(5,6))\end{gathered} \tag{10.1}$$

The indices k,l for all $k,l = 1,\ldots,o$ with $k = l$ are filled up with $m_{k,l} = 1$ because each criterion is exactly as important as the criterion itself. Due to reciprocity, only the criteria k,l above of the diagonal $k > l$ for all $k,l = 1,\ldots,o$ has to be asked. The matrix

$$M = (m_{k,l})_{o\times o} = \begin{array}{c} \\ 1 \\ \vdots \\ k \\ \vdots \\ o \end{array} \begin{array}{c} \begin{matrix} 1 & \cdots & l & \cdots & o \end{matrix} \\ \begin{pmatrix} 1 & \cdots & m_{1,l} & \cdots & m_{1,o} \\ \vdots & 1 & \vdots & \vdots & \vdots \\ \frac{m_{1,l}}{1} & \cdots & 1 & \cdots & m_{k,o} \\ \vdots & \vdots & \vdots & 1 & \vdots \\ \frac{m_{1,o}}{1} & \cdots & \frac{m_{o,k}}{1} & \cdots & 1 \end{pmatrix} \end{array}$$

illustrates these criteria pairs. $m_{k,l}$ is the ratio at how much more, less, or equal a criterion k is in comparison to l. For comparisons, Saaty's scales (see Table 3.1 of Saaty (1977)) were used.

Pairwise Comparison reduced

The PC reduced step is abbreviated by PC_r and refers to the approach of Koczkodaj and Szybowski (2015b) where the number of comparisons is reduced to $o-1$ (see

Chapter 3 for more details). Following Koczkodaj and Szybowski (2015b) and based on the reduced number of PC, the result is an incomplete PC matrix. The pairs to be asked have, furthermore, to fulfill some preconditions mentioned in 3.2.1. Afterwards, an algorithm completes the incomplete PC matrix and is given in Algorithm 1.

In this treatment, the pairs to be asked and the order of the occurrence of these pairs to the respondent are randomized. An example of the pairs to be asked (while the number remains equally) is given in Equation 10.2.

$$((2,5),(4,5),(1,5),(4,6),(3,5)) \tag{10.2}$$

Appropriate to the exemplary pairs given in Equation 10.2 and Equation 3.10 (for solving the resulting linear equation system for the completion Algorithm 1), Equation 10.2 shows the solution to the previously mentioned linear equation system.

$$\begin{aligned}
x_4 &= \log m_{4,5} \\
x_5 &= \log m_{4,6} - \log m_{4,5} = \frac{\log m_{4,6}}{\log m_{4,5}} \\
x_3 &= \log m_{3,5} - \log m_{4,5} = \frac{\log m_{3,5}}{\log m_{3,4}} \\
x_2 &= \log m_{2,5} - \log m_{3,5} = \frac{\log m_{2,5}}{\log m_{3,5}} \\
x_1 &= \log m_{1,5} - \log m_{2,5} + \log m_{3,5} = \frac{\log m_{1,5} * \log m_{3,5}}{\log m_{2,5}}
\end{aligned}$$

With these pairs in mind, it is henceforward possible to complete an incomplete decision matrix as shown in Equation 10.3. The values of Equation 10.2 were used to complete the missing values at first. Next, the transitivity condition

$$\prod_{k=k}^{l} m_{k,k+1}$$

were used to complete missing values where the different between $k, l = 1, \ldots, o$ is $l - k > 1$. The remaining values that are missed are filled up by the reciprocity condition

$$\frac{m_{l,k}}{1}$$

for $k > l$.

$$M = \begin{array}{c} \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \end{array} \begin{array}{c} \begin{array}{cccccc} 1 & 2 & 3 & 4 & 5 & 6 \end{array} \\ \begin{pmatrix} 1 & 10^{x_1} & \prod_{k=1}^{2} m_{k,k+1} & \prod_{k=1}^{3} m_{k,k+1} & m_{1,5} & \prod_{k=1}^{5} m_{k,k+1} \\ \frac{10^{x_1}}{1} & 1 & 10^{x_2} & \prod_{k=2}^{3} m_{k,k+1} & m_{2,5} & \prod_{k=2}^{5} m_{k,k+1} \\ \frac{\prod_{k=1}^{2} m_{k,k+1}}{1} & \frac{10^{x_2}}{1} & 1 & 10^{x_3} & m_{3,5} & \prod_{k=3}^{5} m_{k,k+1} \\ \frac{\prod_{k=1}^{3} m_{k,k+1}}{1} & \frac{\prod_{k=2}^{3} m_{k,k+1}}{1} & \frac{10^{x_3}}{1} & 1 & m_{4,5} & m_{4,6} \\ \frac{m_{1,5}}{1} & \frac{m_{2,5}}{1} & \frac{m_{3,5}}{1} & \frac{m_{4,5}}{1} & 1 & 10^{x_5} \\ \frac{\prod_{k=1}^{5} m_{k,k+1}}{1} & \frac{\prod_{k=2}^{5} m_{k,k+1}}{1} & \frac{\prod_{k=3}^{5} m_{k,k+1}}{1} & \frac{m_{4,6}}{1} & \frac{10^{x_5}}{1} & 1 \end{pmatrix} \end{array} \quad (10.3)$$

It can be seen, the resulting PC matrix is only able to be consistent since a respondent has no chance to construct inconsistencies due to the reduced number of pairs. The algorithm completes this matrix so that the consistency condition is maintained.

PC With or Without Bar Diagram

Diagrams are able to illustrate numbers. They are able to express conditions and relations in a faster and potentially understandable way. Especially when conducting preference elicitation by PC, the overall state over the current preferences might be missing. Without any visualization or additionally provided information, the user is not able to see the ratios or relations among the criteria that were already been judged. Whenever using just PC as preference measurement method, it is not easy to determine the relative importances among judged criteria at a specific time. The PC group without a bar diagram is depicted as D_-. A bar diagram is one possible option to clarify. A bar diagram is able to express the relative importances among the criteria for, say, the priority vector $p = (0.19, 0.08, 0.19, 0.27, 0.15, 0.12)$ (see Chapter 3) as shown in Figure 10.3. When the bar diagram is included into the PC step, then it is depicted as D_+.

Because each respondent can only see the relative importances of the already judged criteria, the bar diagram will be extended during this step. Only after a criterion was part of a pair in the PC, the diagram will contain the corresponding bar. Following this, it is expected that the usage of a bar diagram will bring more clarity into the judgment process. An user might be influenced by the presence of a bar diagram and might rejudge the already judged pairs.

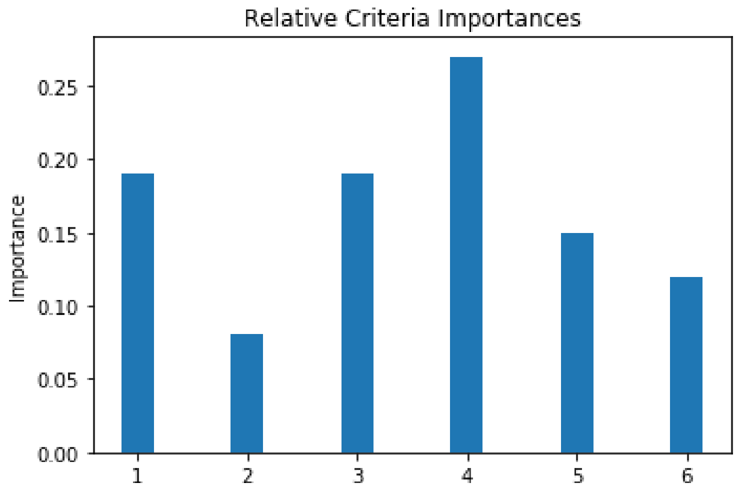

FIGURE 10.3: Example of a bar diagram for relative criteria importances

10.4.2 The Choice Experiment (CE)

This estimator is used in the step *Choice Experiment (CE)* of Figure 10.2. In this step, each respondent is asked four times by a CE to choose one of four alternatives (apartment offers), resulting in four choices of preferred alternatives among four CEs. In each CE, four $c = 0, \ldots, 3$ alternatives $A_{4c}, A_{4c+1}, A_{4c+2}, A_{4c+3} \in A$ were sampled in a randomized way, each with a probability of $1/3^6$ (because there are six criteria with three manifestations for each). The four alternatives ware presented as stimuli in a 2×2 matrix, consisting of all criteria with appropriate (randomized) manifestations. Since this step is a CE, the respondent can only choose one alternative of the presented four, that is one of $A_{4c+1}, A_{4c+2}, A_{4c+3}, A_{4c+4} \in A$ for each CE $c = 0, \ldots, 3$. Further, the binary variable $b^i_{4c+e} \in (0,1)$ indicates whether an alternative of $A_{4c+e} \in A$ where chosen $b^i_{4c+e} = 1$ or not $b^i_{4c+e} = 0$ for each $c = 0, \ldots, 3$ and $e = 1, \ldots, 4$ by respondent i.

Since for each alternative $A_j \in A$ utilities with y^i_j for respondent i are given, the utilities $y^i_{4c+1}, y^i_{4c+2}, y^i_{4c+3}, y^i_{4c+4}$ for the presented alternatives of the CE are also given. The respondent was not able to see any utility. The respondent was just able to see the presented alternatives and was asked to choose one of them. The utilities of all alternatives are mainly based on the PC and the priority vector p^i of respondent i (as described above), which can be achieved by PCV_f (the full design) or PCV_r (the reduced design), depending on the group the respondent is in.

The First Choice Hit Rate

By means of the priority vector p^i of respondent i and the resulting utilities for the 3^6 alternatives $y^i_1, \ldots, y^i_{3^6}$, the FCHR can be estimated by using the chosen alternatives of the CE, i.e., $A_{4c+1}, A_{4c+2}, A_{4c+3}, A_{4c+4} \in A$ for each $c = 0, \ldots, 3$. The FCHR measures the matches between the real choices made by the respondents and the predicted choice, based on the preferences given by PC embedded into the AHP. Then, the FCHR is denoted by $FCHR^i$ for a respondent i, as shown in Equation 10.4. That way, the FCHR is a measure to indicate the goodness of the real choice, given the different predicted utilities across the shown alternatives.

$$FCHR^i = \frac{1}{4} * \left(\sum_{c=0,\dots,3} \frac{\left(\sum_{e=1,\dots,4} b^i_{4c+e} * y^i_{4c+e} \right) - \min_{e=1,\dots,4} y^i_{4c+e}}{\max_{e=1,\dots,4} y^i_{4c+e} - \min_{e=1,\dots,4} y^i_{4c+e}} \right) \tag{10.4}$$

The Equation 10.4 can be understand in such a way that the judgements for the 16th alternatives (A_{4c+e} for the separately displayed CEs $c = 0, \dots, 3$ and the corresponding alternatives included in each CE $e = 1, \dots, 4$) given by a respondent i are first normalized. As the utilities y^i_j already satisfy $0 < y^i_j < 1$ and $\sum_{j=1,\dots,m} y^i_j = 1$, in calculating $FCHR^i$, only the four $e = 1, \dots, 4$ alternatives being present in a CE are considered. The best alternative is weighted with 1 and the worst with 0, other alternatives' weights are between. Put differently, when in the CE with $c = 0$ the alternatives $A_{4c+1}, A_{4c+2}, A_{4c+3}, A_{4c+4} \in A$ are present, the alternative with the highest utility is treated according to $\max_{e=1,2,3,4} y^i_{4c+e} = 1$ and the worst is treated according to $\min_{e=1,2,3,4} y^i_{4c+e} = 0$. Assuming alternative A_{4c+e} was chosen in the CE, then $b^i_{4c+e} = 1$ and $b^i_{4c+e} * y^i_{4c+e} > 0$, and if not, then $b^i_{4c+e} * y^i_{4c+e} = 0$. This ensures that only the chosen alternative is considered. Since it is possible for respondent i to choose a non-optimal alternative $e = 1$ such that $\max_{e=1,2,3,4} y^i_{4c+e} = y^i_{\hat{e}=1,\dots,4 \wedge \hat{e} \neq 1}$, it might be an outcome that $b^i_{4c+e} * y^i_{4c+e} < 1$ for a non-optimal choice. Whenever the choice is optimal, then $b^i_{4c+e} * y^i_{4c+e} = 1$ because the choice among the available alternatives is optimal. After this, Equation 10.4 averages these normalized utilities of the chosen alternatives to $FCHR^i$. Therefore, $FCHR^i$ can be understood as a FCHR of respondent i, based on four judgements across four CE.

10.4.3 Benchmark Using Conjoint Analysis (CA)

As shown in Figure 10.2, the PC is benchmarked against a Conjoint Analysis (CA) (see Section 3.3). The popularity of CA is quite large and it is often used to elicit and to quantify respondents' preferences (Steiner and Meißner, 2018a). The CA is used to quantify the importance of attributes (or criteria). In a next step, the importances derived by CA are compared with those derived by PC.

Since there are $3^6 = 729$ alternatives given, it is not possible to present all alternatives to the respondents in order to ask their for ranking them. Instead of presenting all 729 alternatives (what is meant as full factorial design), a reduced design is used (a fractional factorial design). In this case, a symmetrical and orthogonal design by Plackett and Burman (1946) is used resulting in eight alternatives. These eight alternatives are presented in Table 10.5 where the alternative id is in the column left.

The other columns depict the attribute id that is also shown in Table 10.4. The corresponding values (ids) in the cells of the attribute columns indicate the ids of the attribute levels also shown in Table 10.4.

	Attribute Id					
id	1	2	3	4	5	6
	Attribute Level Id					
1	1	4	9	10	15	18
2	3	4	7	10	13	18
3	1	6	7	10	15	16
4	3	6	9	10	13	16
5	1	4	9	12	13	16
6	3	4	7	12	15	16
7	1	6	7	12	13	18
8	3	6	9	12	15	18

TABLE 10.5: Alternatives (apartment offers) presented in the Conjoint Analysis (CA)

The alternatives presented in Table 10.5 depicts the combinations of attribute levels that are judged by ranking by each respondent. With respect to the reduced design / the fractional factorial design, the number of occurrences of any pair of combined attribute levels is the same. Usually, a full factorial design satisfies this condition but contains too many entries. It is worth mentioning that, according to Plackett and Burman (1946), while presenting the alternatives and the attribute levels, only the minimal or maximal attribute levels are used to construct these eight alternatives. All attribute levels between the first and the last one are omitted.

In the experiment's CA, the respondent has only the ability to rank the alternatives by drag & drop and arrow-down and arrow-top. The alternatives are presented as a table where the row depicts a whole alternative and the columns the attribute levels. That way, the structure is equal to Table 10.5 with replaced attribute ids and attribute level ids by the human-readable format given in Table 10.4 (and without the leading id to avoid confounding effects that might possibly affect the sorting effort). According to this structure, the goal is to sort the alternatives by importance in descending order, i.e., the most important alternative should finally be present on the first rank (on the top) and the worst one on the last rank (on the bottom). The respondents can change the position as often they want.

By means of the CA, the attributes of Table 10.4 are reused and denoted as $C_k \in C$ for the attributes $k = 1, \ldots, o$. In contrast to the part-worth calculation $beta^i_{j,k}$ by the PC as described in Section 10.4.1, with respect to CA, the calculation follows the denotation $\beta^i_{k,h}$, i.e., the part-worth utility of the manifestation $h \in C_k$. For indexing, instead of using j for alternative $A_j \in A$ (in $\beta^i_{j,k}$), in terms of CA, the index h takes place in the range of $h = 1, \ldots, s = |C_k|$. The goal is to estimate the part-worth utilities $\beta^i_{k,h}$. Note that this meaning is exact the same as already introduced in Section

10.4.1 with a basically modified methodology to reach this value. Due to the reduced number of alternatives, not all combinations of attribute levels are given. Following this, for alternative $A_j \in A$, the utility of respondent i is calculated by an additive model

$$y_j^i = \sum_{k=1,\dots,o} \sum_{h=1,\dots,s} \beta_{k,h}^i * b_{j,k,h}$$

where $b_{j,k,h} = 1$ if the level h is present in alternative j for attribute k, and $b_{j,k,h} = 0$ otherwise (see Table 10.5 with the complete enumeration of the alternatives that exist).

To calculate $\beta_{k,h}^i$, the analysis of variance (Backhaus et al., 2016, see page 509) can be and is used for estimating these part-worth utilities. Consequently, it is assumed that the respondents consider the distance between the given ranks to be equal. While the CA task, a respondent i is asked to prioritize all alternatives of Table 10.5. The result is a vector of ranks

$$r^i = (r_j^i)_m = (r_1^i, \dots, r_j^i, \dots, r_m^i)$$

of respondent i where $1 \leq r_j^i \leq m$ and $r_j^i \in \mathbb{N}_+$ depicts the rank of alternative $A_j \in A$. For the alternatives presented in Table 10.5 is $m = 8$. This ranks are judged by each respondent with respect to the alternatives shown in Table 10.5. With these ranks given, a part-worth utility is calculated by

$$\beta_{k,h}^i = \overline{p}_{k,h} - \overline{p}$$

where $\overline{p}_{k,h}$ is meant to be the mean of the ranks of all alternatives $A_j \in A$ where $b_{j,k,h} = 1$. That way,

$$\overline{p}_{k,h} = \frac{1}{\sum\limits_{j=1,\dots,m} b_{j,k,h}} \sum_{j=1,\dots,m} r_j^i * b_{j,k,h}$$

is the sum of the ranks of alternatives $A_j \in A$ where the attribute $C_k \in C$ with the attribute level $h \in C_k$ is present. Similarly means

$$\overline{p} = \frac{1}{m} \sum_{j=1,\dots,m} r_j^i$$

the mean of all ranks given across all alternatives $A_j \in A$. Because the values y_j^i for each alternative $A_j \in A$ are estimated by an analysis of variances, the sum of the squared distance between the estimated y_j^i and the real judgement r_j^i of respondent i for all alternatives $A_j \in A$ is to be minimized $\min_\beta \sum_{j=1,\dots,m} (r_j^i - y_j^i)^2$.

To compare the judgements among all respondents $i \in N$, the part-worth utilities $\beta^i_{k,h}$ need to be normalized. For the normalization, the calculation follows

$$\widehat{\beta}^i_{k,h} = \frac{t(\beta^i_{k,h})}{\sum\limits_{\overline{k}=1,\dots,o} \max\limits_{\overline{h}=1,\dots,s} t(\beta^i_{\overline{k},\overline{h}})}$$

where $\widehat{\beta}^i_{k,h}$ is the normalized part-worth utility of attribute k and attribute level h. It is necessary to transform each $\beta^i_{k,h}$ such that the part-worth utility is transformed by

$$t(\beta^i_{k,h}) = \beta^i_{k,h} - \min_{\overline{h}=1,\dots,s} \beta^i_{k,\overline{h}}$$

to be 0 for the lowest attribute level h for each attribute k. The normalized part-worth utility $\widehat{\beta}^i_{k,h}$ is then in the range of $0 \leq \widehat{\beta}^i_{k,h} \leq 1$ and the sum of the most preferred alternative is 1 because it consists of the most preferred attribute levels for each attribute.

One goal of the CA is to represent a benchmark to the PC. To be able to act as a benchmark, the importances on the level of attributes are required. Therefore, on the basis of the normalized part-worth utilities $\widehat{\beta}^i_{k,h}$, the relative importances for the attributes are derived by

$$p^i_k = \frac{\max\limits_{h=1,\dots,s} \widehat{\beta}^i_{k,h}}{\sum\limits_{\overline{k}=1,\dots,o} \max\limits_{\overline{h}=1,\dots,s} \widehat{\beta}^i_{\overline{k},\overline{h}}}$$

where with p^i_k the same notation is used as for the priority vector introduced in Section 10.4.1, i.e., the relative importance of attribute (or, in a multi-criteria sense, criteria) k of respondent i such that $\sum_{k=1,\dots,o} p^i_k = 1$. As described by Backhaus et al. (2016), the span of the part-worth utilities are used in order to express the importance of an attribute. That way, attribute levels that are associated with a high part-worth utilities in relation to others, are more important with respect for varying the importances of attributes. For the benchmark, the procedure does not differ from the procedure that is used for the PC, as described in Section 10.4.2. The priority vector p^i of respondent i exists therefore twice – on the one hand, it is achieved by the CA and, on the other hand, by PC. Both methods end up with a vector of importances across the attributes (criteria), that can be used for comparison purposes.

10.5 Experimental Results

The experiment was conducted on February 7, 2020 as online experiment and took around 45 hours until 438 respondents were recruited successfully. On the basis of these 438 respondents, only 431 respondents could be used since the others had not responded truthfully or had answered control questions wrong. The Figure 10.4

shows the histogram of how the participation is distributed across the overall duration of the experiment.

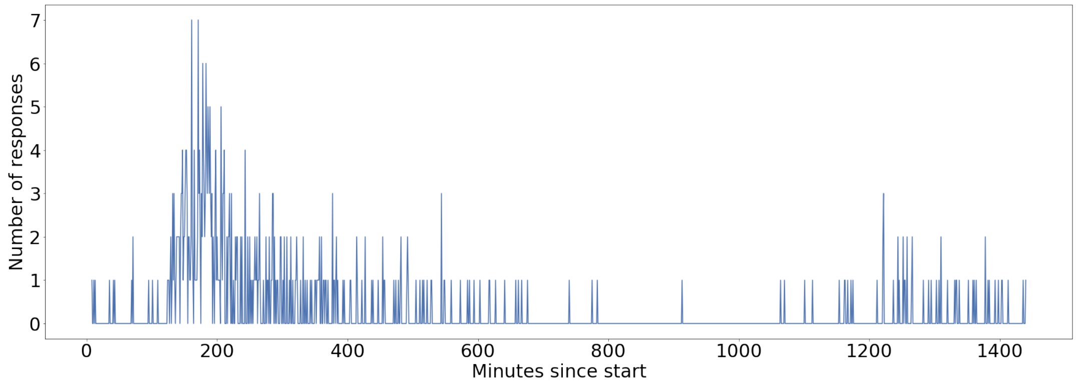

FIGURE 10.4: Responses per minute (values at the x-axis show the number of minutes elapsed since start of the experiment, values at y-axis the number of responses per minute)

While PC_f represents the baseline of the experiment, showing the full design of PC of the AHP, PC_r means a treatment using a reduced design of PC of the AHP. Further, D_- indicates that a group is not confronted with a bar diagram while D_+ indicates the opposite. Beyond this, PC_f contains both groups with D_+ and without D_- diagram where also the baseline PC_f is given. This is attributed to the fact that some groups are combined for extended analysis. Equally, PC_f contains both groups with D_+ and without D_- diagram where also the treatment PC_r is given. According to the same principle, D_+ contains those where the baseline PC_f and the treatment with the reduced design PC_r is present. Equally again, D_- contains those where the baseline PC_f and the treatment with the reduced design PC_r is present. Consequently, PC_f and PC_r consist of two groups either, whilst D_+ and D_- also consist of two groups either. It should be added that, due to two groups are merged, it cannot be definitely explained where the effect comes from, although a higher samples gives clearer results and is more selectively.

In the experiment were three questionnaires used, the NASA TASK LOAD INDEX (TLX), the Big Five-Inventory (BFI)-10, and the Preference for Consistency Scale (PCS). Based on the evaluation of the results, only the TLX has reached utilizable results with respect to the treatments, as the questionnaires BFI and PCS did not add utility in these cases of treatments. Anyway, the questionnaire Big Five-Inventory (BFI)-10 shows that, across all groups PC_fD_-, PC_fD_+, PC_rD_-, and PC_rD_+, the respondents does not differ by their personalities. With respect to the PCS and across the groups, the respondents are equally distributed again.

10.5.1 Sample

For the experiment, students of the KD^{2}Lab [7] pool have been recruited. This pool is considered as population of our sample. The sample, in turn, was selected randomly (random sample).

Gender	*Abs. Count*	*Rel. Count*	*Group*		
			Group	*Abs. Count*	*Rel. Count*
Female	150	34.80%	PC_f & D_-	43	9.97%
			PC_f & D_+	36	8.35%
			PC_r & D_-	38	8.81%
			PC_r & D_+	33	7.65%
Male	281	65.19%	PC_f & D_-	68	15.77%
			PC_f & D_+	66	15.31%
			PC_r & D_-	73	16.93%
			PC_r & D_+	74	17.16%

TABLE 10.6: Gender distribution of the sample

In Table 10.6, the gender distribution of the sample can be seen. The respondents being male are a little more in the sample. Further, the table shows that the gender distribution across the groups is, overall, balanced. With respect to the distribution of education, Table 10.7 shows that the most respondents have education of High-School Diploma, Bachelor, and Master.

Education	Abs. Count	Rel. Count
High-School Diploma	216	50.11 %
Bachelor	163	37.81 %
Master	42	9.74 %
Diploma	3	0.69 %
Magister	3	0.69 %
Vocational Education	3	0.69 %
State Examination	1	0.23 %
No Education	0	0.00 %

TABLE 10.7: Education distribution of the sample

Further, in Figure 10.5 the absolute distribution of the respondents year of birth is given with 30 bins. For the year of birth, the mean is at $\overline{birth} = 1995.80$ and the standard deviation is at $s_{birth} = 4.55$.

In Figure 10.6, the absolute distribution of the respondents' year of last apartment search is given (with 30 bins). For the last year of apartment search, the mean is at $\overline{las} = 1.72$ and the standard deviation is at $s_{las} = 2.13$. Consequently, the majority of

[7] The KD^{2}Lab is a laboratory founded by the DFG (Deutsche Forschungsgemeinschaft) and offers a pool of over 4000 registered students to participate in experiments.

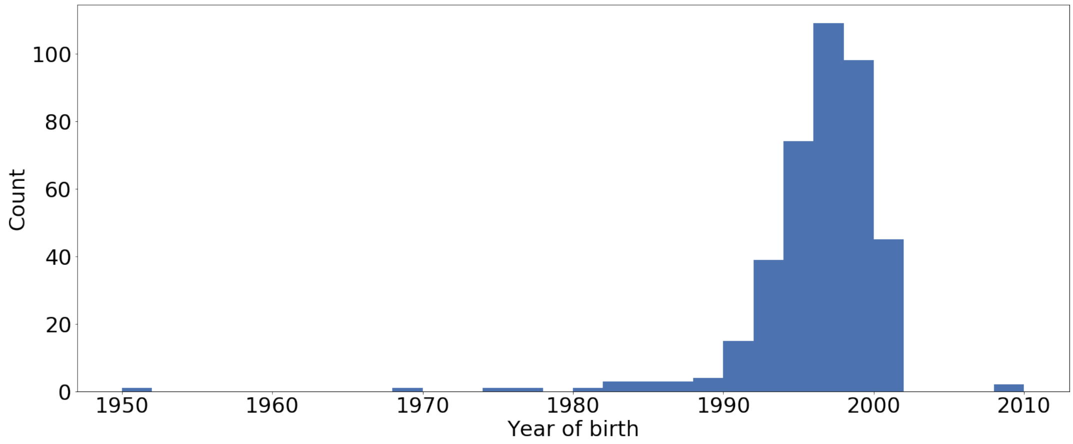

FIGURE 10.5: Absolute distribution of the respondents' year of birth

the respondents of the sample were facing an use case they are familiar with and it is assumed that is was easier for them to put themselves in the imagination. Whenever the respondents stated 0 as value for the last looking for a free apartment, they are currently looking for. As shown in Figure 10.7, the younger the respondents were, the shorter the duration to their last time they were looking for an apartment. Beyond these respondents who were familiar with looking for a new apartment, there were also 29 respondents who never looked for a new apartment, starting from year of birth 1989 (minimum) until 2001 (maximum) with a mean at 1997.

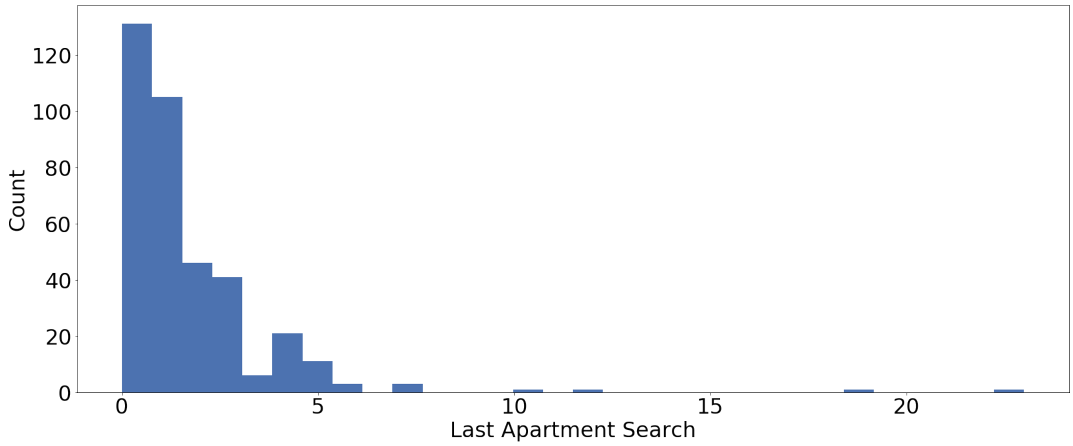

FIGURE 10.6: Absolute distribution of the respondents' last apartment search in years

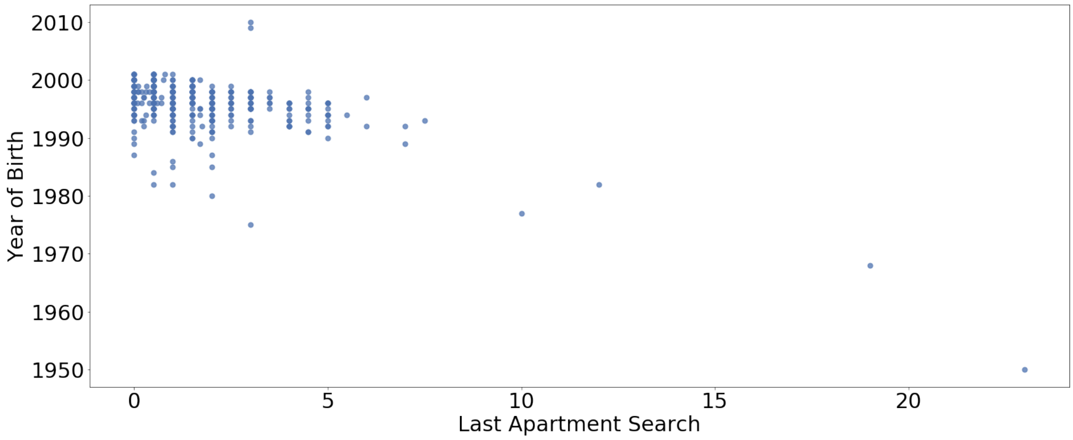

FIGURE 10.7: Relation between date of birth and last search for an apartment

10.5.2 The First Choice Hit Rate

Since this experiment has a 2×2 design, two exogenous variables are used. As result, four groups were planned and, for each group, a dedicated sample was elicited. Table 10.8 shows the key figures for the groups and the merged groups with respect to the FCHR (where the utility is predicted by PC), which is introduced in Section 10.8. The table shows for the averaged FCHR, the statistical standard deviation s, the mean $\overline{\text{FCHR}}$, the min and max values, and the quantiles $Q25$, $Q50$ (median), and $Q75$ for each group. The averaged FCHR is represented by $FCHR^i$ for respondent i (for calculation and meaning, please note Section 10.4.2).

Group	Size	s	$\overline{\text{FCHR}}$	Min	Q25	Median	Q75	Max
PC_fD_-	111	0.126	0.878	0.424	0.814	0.911	0.996	1.0
PC_rD_-	111	0.143	0.855	0.420	0.761	0.884	0.991	1.0
PC_fD_+	102	0.121	0.898	0.551	0.805	0.959	1.000	1.0
PC_rD_+	107	0.167	0.850	0.184	0.787	0.893	0.984	1.0
PC_r	218	0.155	0.852	0.184	0.780	0.887	0.987	1.0
PC_f	213	0.124	0.888	0.424	0.809	0.930	1.000	1.0
D_-	222	0.135	0.867	0.420	0.795	0.900	0.995	1.0
D_+	209	0.148	0.873	0.184	0.790	0.919	1.000	1.0

TABLE 10.8: Overview of the First Choice Hit Rate (FCHR) of the groups

As an extension to Table 10.8 and to put insights in more detail, the box plot diagram given in Figure 10.8 shows the dedicated groups and merged groups as box plots. The plotted values are according to the values contained by Table 10.8. The box plots are sorted by the median in descending order of that table 10.4.2. The diagram figures out that the treatment PC_rD_- performed worst, i.e., for the given sample, whenever the reduced design of PC in combination with a missing bar diagram is used, the accuracy rate compared to the other groups and merged groups is worse. The second worst group is the merged group PC_r where those with and without bar diagram (D_+ and D_-) are contained by. Being consistent to the observations until now, the third worst group is the treatment $\text{PC}_r D_+$, i.e. the reduced design with bar diagram.

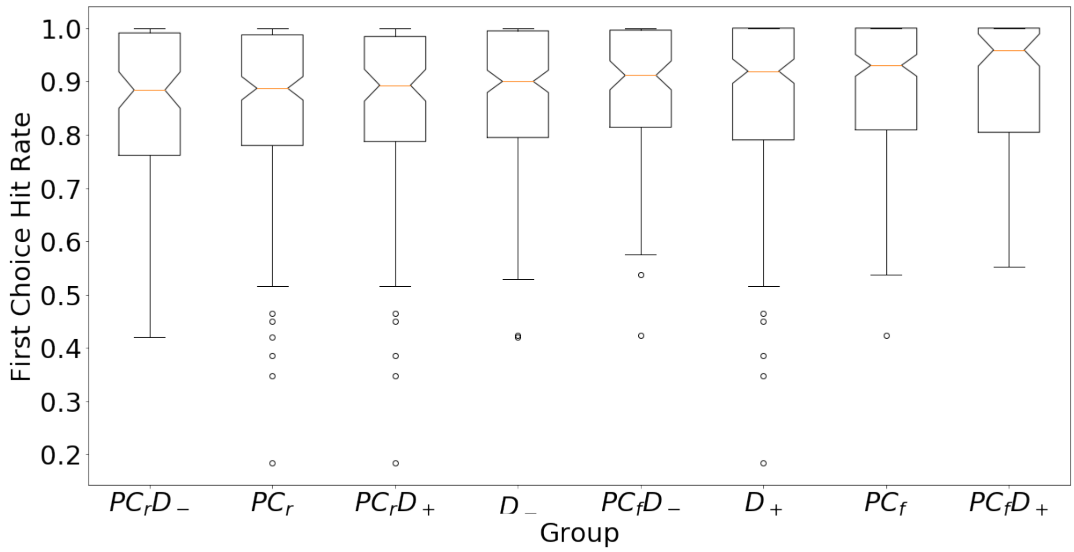

FIGURE 10.8: Box plot showing data points and quartiles for the (aggregated) groups

Up to this point, PC_r and $\text{PC}_r D_+$ have strong outlier as depicted by the minimal values of 0.184 at $\text{PC}_r D_+$, PC_r, and D_+. The best (merged) group is $\text{PC}_f D_+$, the baseline with a bar diagram present. It can be observed that each group is better when using a bar diagram in comparison to any treatment where the reduced design of PC is used. Once the reduced design is used in combination with a bar diagram, the FCHR, among the treatments where the reduced design is involved, are the best. Consequently, when the reduced PC is used, a bar diagram is helpful to mitigate the negative effect. Further, when the full design of PC is used, the accuracy rate is better in general. When the full design of PC is combined with a bar diagram $\text{PC}_f D_+$, the maximal accuracy rate is reached.

A further impression is given with the cube plot of Figure 10.9. The cube plot represents the 2×2 experiment design with the corresponding baseline and treatments. This diagram shows, similar to the box plot of Figure 10.8, that the PC_r reaches less than PC_f, i.e., the FCHR performs slightly worse. In more detail, the (non-standardized) effect of $\text{PC}_f D_-$ to $\text{PC}_r D_-$ is $\Delta(\text{PC}_f D_- \wedge \text{PC}_r D_-) = -0.023$, that is by using a reduced PC without bar diagram, the accuracy rate is worse by -0.023 in comparison to the full design without a bar diagram. When now a bar diagram is present, the effect of $\text{PC}_f D_+$ to $\text{PC}_r D_+$ is $\Delta(\text{PC}_f D_+ \wedge \text{PC}_r D_+) = -0.048$. That means, if the bar diagram is present, the (non-standardized) effect is bigger. By the sum of both simple effects and division by two, the main (non-standardized) effect of the PC full vs. reduced is derived ${}^{\Delta(\text{PC}_f D_- \wedge \text{PC}_r D_-) + \Delta(\text{PC}_f D_+ \wedge \text{PC}_r D_+)}/_2 = \Delta(\text{PC}_f \wedge \text{PC}_r) = -0.035$.

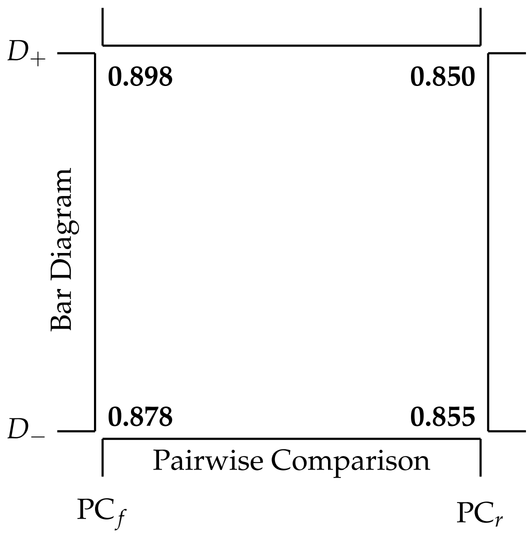

FIGURE 10.9: Cube Plot showing the treatment effects

Based on the baseline $PC_f D_-$, when the bar diagram is treated $PC_f D_+$, the (non-standardized) effect is $\Delta(PC_f D_- \wedge PC_f D_+) = 0.019$, i.e. when using the full design of PC, the presence of a bar diagram can help slightly to enhance the FCHR. With regard to the reduced design of PC, $\Delta(PC_r D_- \wedge PC_r D_+) = -0.005$, the effect is negative but low, showing that the accuracy rate has slightly deteriorated. The main effect of having a bar diagram in is given by $\Delta(PC_{f}D_- \wedge PC_{f}D_+) + \Delta(PC_{r}D_- \wedge PC_{r}D_+)/2 = \Delta(D_- \wedge D_+) = 0.007$. That is, overall, treating PC with a bar diagram increases the accuracy rate of FCHR slightly positive. As also shown by Table 10.9 in column *Simple Effect* and to summarize this insights shortly, the treatment PC_r has yield a slight deterioration while the treatment with a bar diagram D_+ has yield a slightly improvement.

Baseline	Treatment	(Simple) effect	Effect size (d)	U-test	T-test
$PC_f D_-$	$PC_r D_-$	-0.024	-0.174	0.277	0.195
$PC_f D_+$	$PC_r D_+$	-0.048	-0.327	0.041 *	0.019 *
$PC_f D_-$	$PC_f D_+$	0.019	0.155	0.183	0.259
$PC_r D_-$	$PC_r D_+$	-0.005	-0.033	0.875	0.807
PC_f	PC_r	-0.035	-0.251	0.029 *	0.009 **
D_-	D_+	0.006	0.046	0.329	0.635

TABLE 10.9: Effects on First Choice Hit Rate (FCHR)

Since the afore-mentioned effects are non-standardized, standardized effects reveal information about the comparability of these effects. Table 10.9 shows in column *Effect size (d)* the standardized effect by Cohen (2013) of the respective groups. According to this, the standardized effect size (d) is calculated by

$$d(x_1, x_2) = \frac{\overline{x_1} - \overline{x_2}}{\sqrt{\frac{s_1^2 + s_2^2}{2}}}$$

where two samples x_1 and x_2 with equal sizes are assumed to be given with different variances $s_i^2 = \frac{1}{n-1}\sum_{j=1}^{n}(x_{j,i} - \overline{x_i})$ and the average $\overline{x_i}$ of a sample i. With respect to the original classification of Cohen (1988) and an extended version of Sawilowsky (2009), Table 10.10 shows the effect sizes with their respective range they belong to.

Effect size	Effect size (d)	by
	$d < 0.01$	
Very Small	$0.01 \leq d < 0.20$	Sawilowsky (2009)
Small	$0.20 \leq d < 0.50$	Cohen (1988)
Medium	$0.50 \leq d < 0.80$	Cohen (1988)
Large	$0.80 \leq d < 1.20$	Cohen (1988)
Very large	$1.20 \leq d < 2.0$	Sawilowsky (2009)
Huge	$d \geq 2.0$	Sawilowsky (2009)

TABLE 10.10: Effect sizes by Cohen (1988) and Sawilowsky (2009)

This classification scheme given, the groups PC$_f D_-$ versus PC$_r D_-$, PC$_f D_-$ versus PC$_f D_+$, PC$_r D_-$ versus PC$_r D_+$, and D_- versus D_+ have shown a *small* effect. The groups PC$_f D_+$ versus PC$_r D_+$, and PC$_f$ versus PC$_r$ have shown a *medium* effect size. No group has shown a large standardized effect size by Cohen (1988).

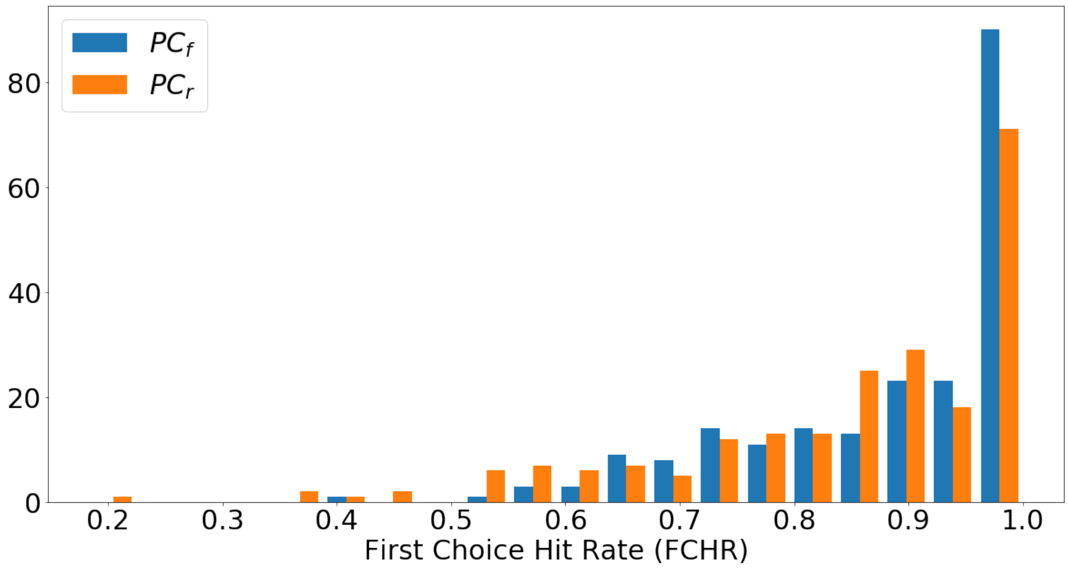

FIGURE 10.10: Histogram of the First Choice Hit Rate (FCHR) of Pairwise Comparison (PC) full versus reduced

As shown in the histogram of Figure 10.10, the distribution for both PC$_f$ and PC$_r$ is left-skewed. This observation given, a statistical test to examine the statistical effect have to be non-parametric. Since there were two independent samples given, both have a left-skewed distribution, the Mann-Whitney rank test (Mann and Whitney, 1947) is recommended (Sheskin, 2000) due to their skewness. That way, column *U-test* of Table 10.9 shows the *p-value* of the Mann-Whitney rank test. The format follows the style of American Psychological Association (APA), indicating the level of the statistical significance by the number of asterisks, i.e., the significance code for the declared p-values for $p \leq .05$ is *, $p \leq .01$ is **, $p \leq .001$ is ***, and $p \leq .0001$ is ****.

Considering these p-values with the afore-mentioned declarations, there are statistical significances at PC_f versus PC_r with one asterisks (*) and one further at $\text{PC}_f D_+$ versus $\text{PC}_r D_+$ with one asterisks (*). For the sake of completeness and for comparison purposes, the results of the applications of the Student's test (Sheskin, 2000) are given in column *T-test* with almost the same effect declarations by asterisks. Merely the effect size of PC_f versus PC_r is higher by one asterisks (**).

10.5.3 Correlation Between Conjoint Analysis Versus Pairwise Comparison

The experiment consists of a Conjoint Analysis (CA) task that took place either at first or as second step. The CA task was used as benchmark to the PC. That way, the achieved importances per criteria can be further examined. Both approaches, the CA and the different designs of PC, end up with a priority vector p^i for a respondent i. Because the PC design is treated to be reduced PC_r instead of full PC_f, these differences can further be inspected with respect to the resulting importances per criteria (the same holds for the treated bar diagram D_- versus D_+). To bring both vectors p^i for analysis together, the Perarson correlation coefficient is calculated since the data show no strong outlier in general and are present in a metric scale. The analysis by Spearman rank-order correlation coefficient showed similar results. As introduced in Section 10.4.1, let denote the priority vector p^i created by PC with p^i_{PC} in general, $p^i_{\text{PC}_f}$ with respect to the full design PC_f, and $p^i_{\text{PC}_r}$ with respect to the reduced design PC_r, $p^i_{\text{PC}_f D_+}$ in the case if a bar diagram is present and $p^i_{\text{PC}_f D_-}$ if not. Whenever the priority vector is derived by the CA, p^i_{CA} denotes that the importances of the priority vector are achieved by means of CA. To indicate that the priority vector p^i_{CA} was created by a respondent who was in the $\text{PC}_f D_-$ group, the priority vector derived by CA is indicated by $p^i_{\text{CA}_f D_-}$. The Pearson correlation coefficient is indicated by r. To indicate the correlation coefficient for the group $\text{PC}_f D_-$, the both priority vectors are used in combination. Then a function $r : \mathbb{R}^o \times \mathbb{R}^o \rightarrow \mathbb{R}$ returns the Pearson correlation coefficient $r(p^i_{\text{PC}_f D_-}, p^i_{\text{CA}_f D_-})$, where o indicates the number of criteria (attributes).

Table 10.11 shows the Pearson correlation coefficients across all elicited groups with respect to their key figures. For this purpose, the priority vector $p^i_{\text{CA}_{group}}$ of the CA of a respondent i is used and is combined with priority vector $p^i_{\text{PC}_{group}}$, i.e., for each respondent i, a correlation coefficient $r(p^i_{\text{PC}_{group}}, p^i_{\text{CA}_{group}})$ is created.

In Table 10.12, the effect sizes are mentioned. The content of the table reveals similarities to the content of Table 10.9 showing the effects with respect to the FCHR and, therefore, support the results. Further, the histogram of Figure 10.11 shows a similar left-skewed distribution for the Pearson correlation coefficient with respect

Group	Len	Var	Mean	Min	Q25	Median	Q75	Max
PC_fD_-	113	0.144	0.592	-0.807	0.396	0.699	0.891	0.994
PC_rD_-	114	0.204	0.474	-0.753	0.141	0.648	0.857	0.990
PC_fD_+	104	0.113	0.655	-0.652	0.511	0.773	0.910	0.995
PC_rD_+	107	0.159	0.476	-0.603	0.199	0.540	0.835	0.991
PC_r	221	0.182	0.475	-0.753	0.172	0.565	0.853	0.991
PC_f	217	0.130	0.622	-0.807	0.476	0.739	0.899	0.995
D_-	227	0.177	0.533	-0.807	0.273	0.678	0.881	0.994
D_+	211	0.144	0.564	-0.652	0.348	0.688	0.880	0.995

TABLE 10.11: Overview of Pearson coefficient of the groups

to the groups PC_f versus the PC_r. The group PC_f is slightly better than the reduced one PC_r. Table 10.12 shows with column *(Simple) effect* the (Simple) effect. The effect $\Delta(\text{PC}_fD_- \wedge \text{PC}_fD_+) = 0.056$ is positive only if a bar diagram is in use. The effect is a little bit fewer if the full and reduced samples are merged, i.e. $\Delta(D_- \wedge D_+) = 0.016$, because the effect of $\Delta(\text{PC}_rD_- \wedge \text{PC}_rD_+)$ is slightly negative.

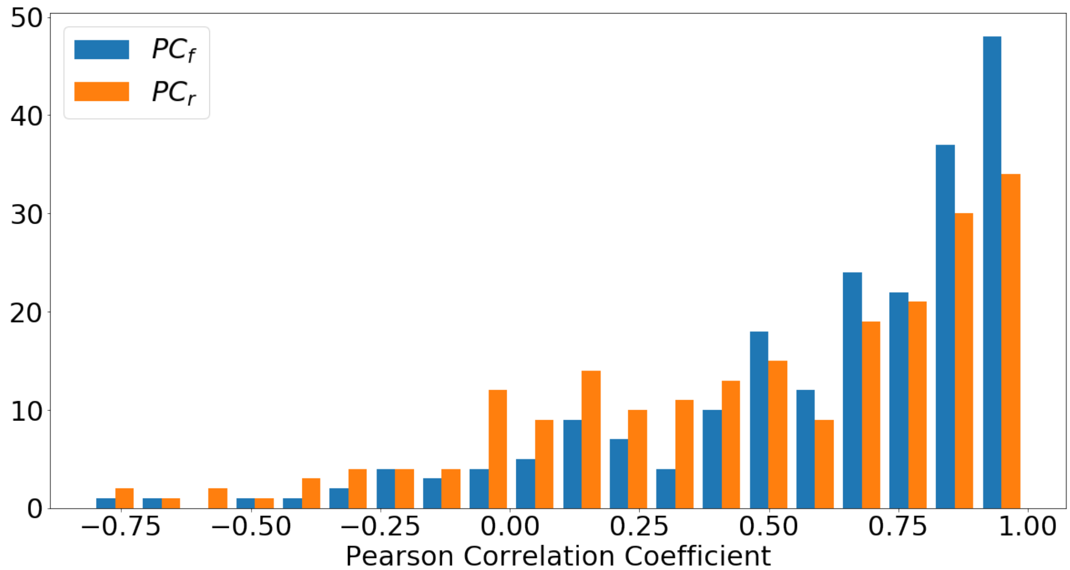

FIGURE 10.11: Histogram of the Pearson correlation coefficient between Conjoint Analysis (CA) and Pairwise Comparison (PC) full versus reduced

There are statistical significances at PC_f versus PC_r with one asterisks (*) by the U-test and two asterisks (**) by the T-test, and one further at PC_fD_+ versus PC_rD_+ with one asterisks (*). It is worth mentioning that the evaluation with the Pearson correlation coefficient between the PC and the CA is consistent to the evaluation with respect to the FCHR. Interpreting all values in a ordinal sense, there would not occur differences at all.

Figure 10.12 contains two scatter plots. These scatter plots show where the FCHR is given for both the CA as benchmark and the PC as instrument under question. The upper plot shows the values for the group with the highest effect size on the Pearson

Baseline	Treatment	(Simple) effect	Effect size (d)	U-test	T-test
$PC_f D_-$	$PC_r D_-$	-0.098	-0.239	0.13	0.077
$PC_f D_+$	$PC_r D_+$	-0.174	-0.469	0.001 ***	0.001 ***
$PC_f D_-$	$PC_f D_+$	0.064	0.176	0.237	0.201
$PC_r D_-$	$PC_r D_+$	-0.012	-0.029	0.618	0.831
PC_f	PC_r	-0.135	-0.344	0.001 ***	0.0 ***
D_-	D_+	0.024	0.059	0.716	0.537

TABLE 10.12: Effects on the Pearson correlation coefficient between Conjoint Analysis (CA) and Pairwise Comparison (PC)

correlation coefficient as shown in Table 10.12, that is $PC_f D_+$ versus $PC_r D_+$. That upper scatter plot explains that the most values for the FCHR are high for the CA and the PC, respectively. Both have a high correlation since they are distributed equally. While the dots in the upper scatter plot show the respective FCHR value, the triangles depict the mean of the FCHR for these FCHR values. As shown, the benchmark CA delivered the same results in both groups as the triangles are on the same hight (vertically), supporting the assumption that the CA is a good reference point and benchmark. The mean of $PC_r D_+$ is slightly left to the mean of the $PC_f D_-$, suggesting that the performance of the reduced design of PC is slightly worse than the full design of PC.

The bottom scatter plot of Figure 10.12 shows the same axes as the upper scatter plot but with a changed range of values on both axes. The bottom scatter plot shows the quantiles 0.25, 0.5 (median), and the 0.75. Within the bottom scatter plot, the samples $PC_f D_-$, $PC_r D_-$, $PC_f D_+$, and $PC_r D_+$ are shown for the mentioned quantiles.

To extend this analysis, Table 10.13 shows the comparison between the several samples of PC with respect to the accuracy rate of CA, measured by the FCHR. Both the PC and CA are used to derive an accuracy rate, operationalized to FCHR. The values show two statistical significances with one asterisks (*) at $PC_f D_+$ compared with those CA results. The simple effect is at -0.045, indicating that the CA performs worse than the $PC_f D_+$ in the FCHR (standardized at -0.344, a small effect). The statistical significance at PC_f compared to CA on FCHR supports this observation.

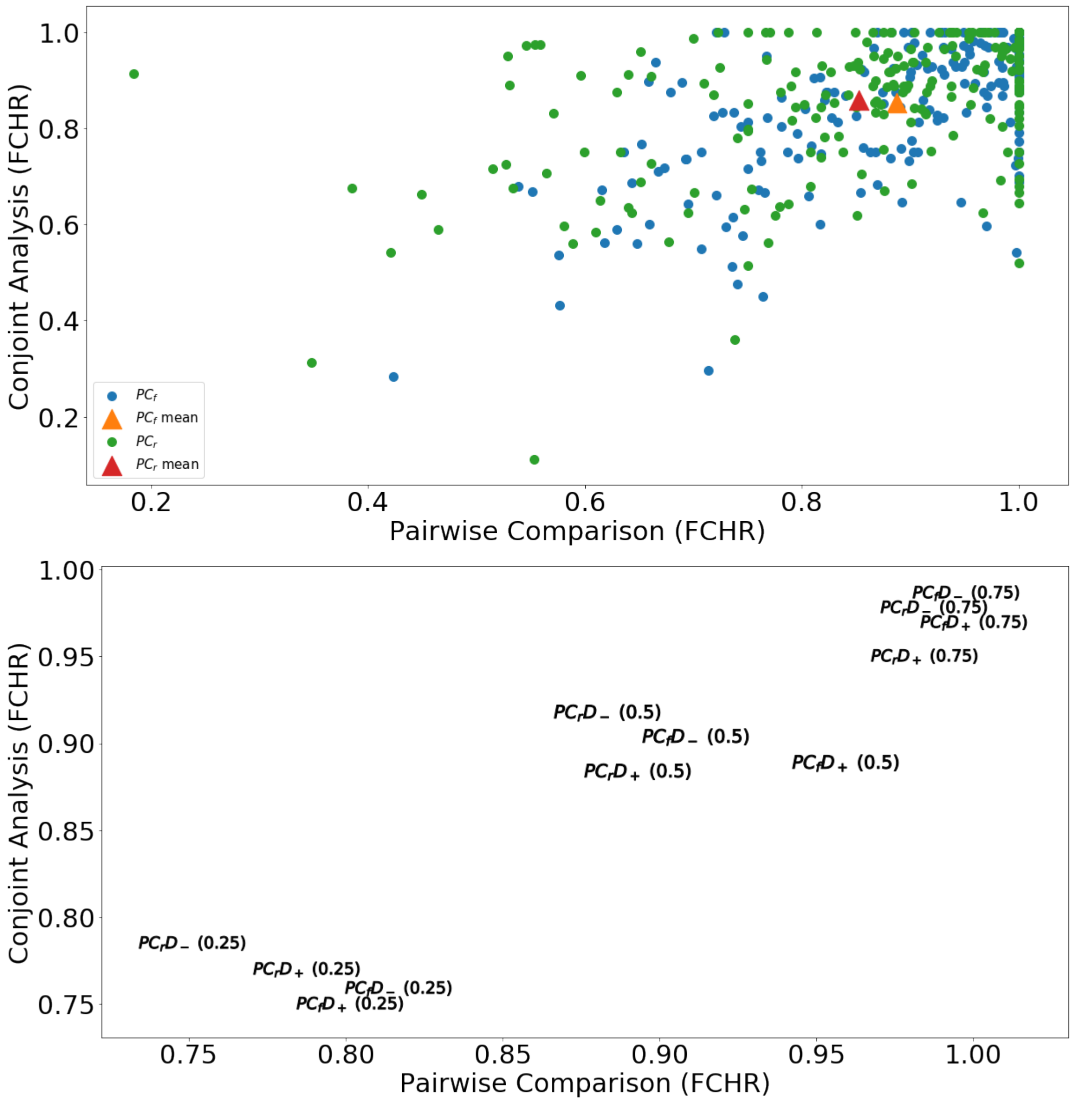

FIGURE 10.12: Scatterplot with First Choice Hit Rate (FCHR) for Conjoint Analysis (CA) contrasting to Pairwise Comparison (PC)

Sample	Simple Effect	Effect size (d)	U-test	T-test
PC_fD_-	-0.023	-0.162	0.477	0.229
PC_rD_-	0.013	0.089	0.325	0.508
PC_fD_+	-0.045	-0.344	0.011 *	0.015 *
PC_rD_+	-0.001	-0.008	0.399	0.955
PC_r	0.006	0.041	0.911	0.669
PC_f	-0.033	-0.246	0.024 *	0.012 *
D_-	-0.005	-0.033	0.877	0.727
D_+	-0.023	-0.158	0.016 *	0.107

TABLE 10.13: FCHR of the Pairwise Comparison (PC) samples in comparison with Conjoint Analysis (CA)

10.5.4 Time Required for and Complexity of Pairwise Comparison

One assumption is that the reduced design PC_r is able to save time in comparison to the full design PC_f. This assumption is examined by time elapsed between the start of the PC task and the end of the PC task. That way, the upper distribution shown in Figure 10.13 shows both curves, i.e. PC_f versus PC_r, where the x-axis consists of the total seconds of the PC task. The bottom distribution shows the observed effect between $PC_r D_-$ versus $PC_r D_+$.

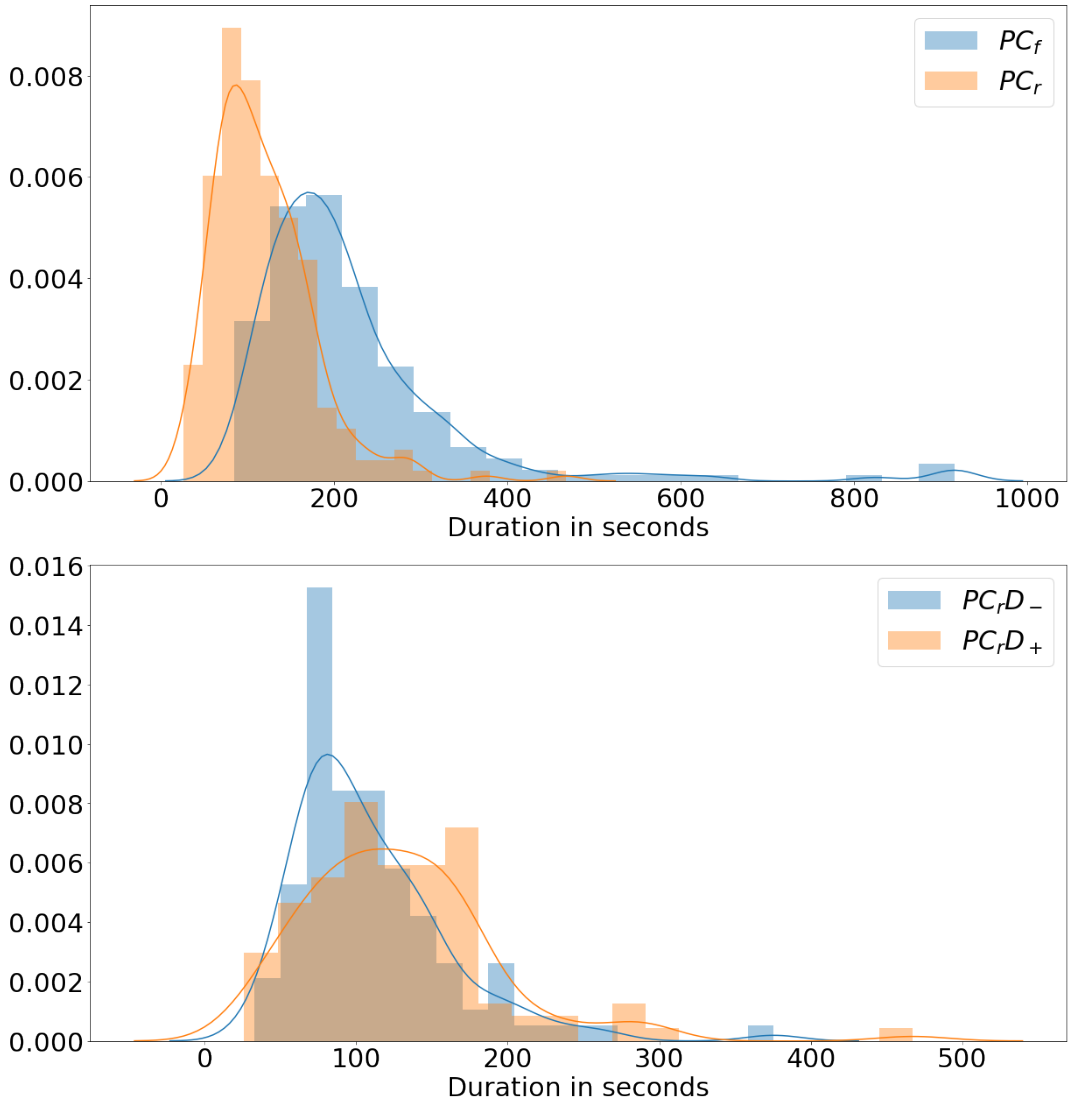

FIGURE 10.13: Distribution of duration of the PC task ((PC_f versus PC_r) and $PC_r D_-$ versus $PC_r D_+$)

As shown in the upper diagram of Figure 10.13, the distribution of PC_r is more left meaning that it took less time to conduct the PC task for the respondents. This observation corresponds to the expectation because the number of pairs of the reduced PC design consists of less pairs. The total duration is decreased while the duration for exactly one pair to be judged holds equally. Beyond this, the duration mean of PC_f is 220.458 seconds while the duration mean of PC_r is 118.841 seconds.

That is, the simple effect size is $\Delta(\text{PC}_f \wedge \text{PC}_r) = -101.616$ seconds and the standardized effect size by Cohen (2013) is $d_{\text{PC}_f \wedge \text{PC}_r} = -1.014$ (large effect by Cohen (2013)) and as depicted by Table 10.10. The (standardized) effect sizes, as well as results of the U-test and the T-test, are also given by Table 10.14.

Baseline	Treatment	Simple Effect	Effect size (d)	U-test	T-test
PC_fD_-	PC_rD_-	-109.986	-0.982	0.0 ***	0.0 ***
PC_fD_+	PC_rD_+	-92.975	-1.082	0.0 ***	0.0 ***
PC_fD_-	PC_fD_+	1.684	0.013	0.037 *	0.925
PC_rD_-	PC_rD_+	18.696	0.317	0.011 *	0.02 *
PC_f	PC_r	-101.616	-1.014	0.0 ***	0.0 ***

TABLE 10.14: Effects sizes of the duration of the PC task

AS shown in the bottom diagram of Figure 10.13, even with respect to the bar diagram treatment PC_rD_- versus PC_rD_+, a statistical significance was observed (while PC_fD_- versus PC_fD_+ has no significance). The presence of a bar diagram seems to increase the time required by the PC task at $\Delta(\text{PC}_rD_- \wedge \text{PC}_rD_+) = 18.696$ seconds and $d_{\text{PC}_rD_- \wedge \text{PC}_rD_+} = 0.317$ (medium effect by Cohen (2013)). Further, the presence of a bar diagram treatment while having the full design given PC_fD_- versus PC_fD_+ seems not to have statistical significance or an effect.

Another assumption is related to perceived complexity, operationalized to the self-reported cognitive load and elicited by the questionnaire NASA TASK LOAD INDEX (TLX). Beyond the cognitive load of each respondent, the questionnaire consists of multiple items covering the overall workload of the respondents. The questionnaire is made up of six questions covering the topics (1) *Mental demand*, (2) *Physical demand*, (3) *Temporal demand*, (4) *Performance*, (5) *Effort*, (6) *Frustration level*.

With respect to the questionnaire TLX, it is possible to put a weight in the range of $[-20, \ldots, 0, \ldots, +20]$ (boundaries included) where the left corner means "less" and the right corner means "more". The respondents were able to express indifference by putting the weight at 0, i.e. the mid value. For analysis, the respondents' weights are normalized for each question to be in $[-50, +50]$ (boundaries included). The whole questionnaire is shown in the appendix in Section A.1.1. Figure 10.14 shows a bar diagram where the respective mean for each question and of each group is displayed. For this, the numbers afore-mentioned (in brackets before the six question topics are listed) are reused to refer to the question shown. The first observation is that no respondent was faced with a high workload during the PC task (each mean value is below 0, that is the side indicating "less"). It can be seen that the first topic, that is mental demand, has reached the highest value across all groups (relatively high mental demand compared with other topics). Group PC_fD_- has reached the highest value for this question, that is the respondents of group PC_fD_+ are faced with a relatively high mental demand. Respondents been assigned the reduced version of PC with a bar diagram present PC_rD_+, have reached the lowest value for

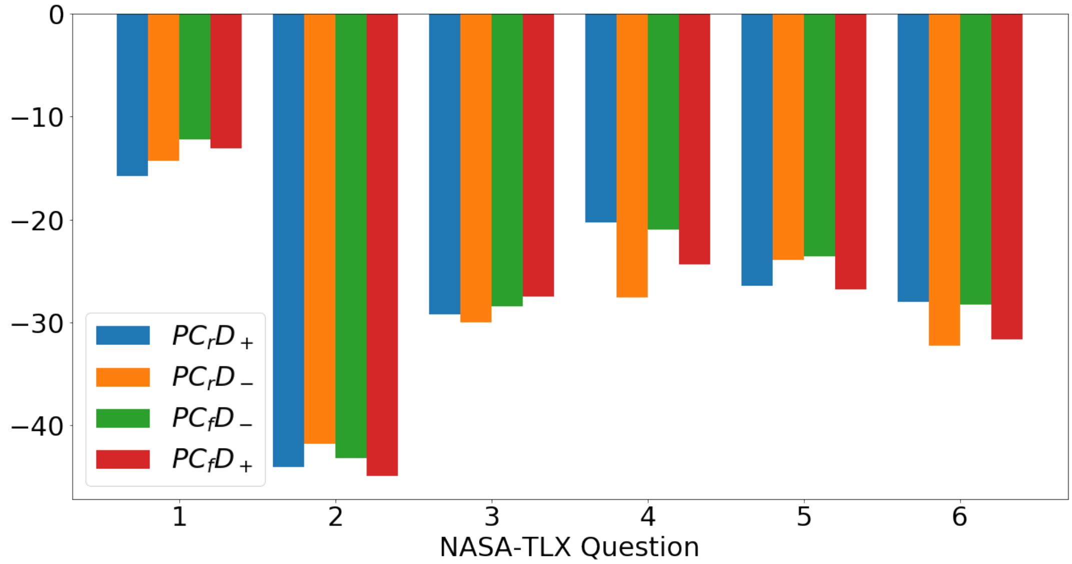

FIGURE 10.14: Bar chart showing mean values for each NASA TASK LOAD INDEX (TLX) question of each group PC_fD_-, PC_fD_+, PC_rD_-, PC_rD_+

question 1, meaning that – based on the answers – the reduced design of PC PC_rD_+ with a bar diagram present lead to a less mental demand. In addition, as shown in Table 10.15, the standardized effect of PC_fD_+ to PC_rD_+ has reached the highest value and is just *very small* (see Table 10.10). The *p-value* for neither the U-test nor the T-test have reached a statistical significance, i.e., the distributions distinction is not sufficient to assumed different populations.

Next, and less surprising, question 2 covering the topic *physical demand* has reached very small values across the groups (less physical demand). The respondents were just asked to do a Human–computer interaction (HCI) while working on the experiment. This is why a physical demand is improbable and, by observation, does not happen. The question belongs to the original version of the TLX questionnaire, this is why the question was present. Since the question has no high importance, supported by empirical evidence, the question values does not occur in any further analysis, and are not part of Figure 10.15. Question 3 *temporal demand* reached

Relating the next question *temporal demand*, indicated by number 3, there was no differences between the groups observed. Further, the mean values are between -20 and -30, expressing the demand to be between less and indifferent. Since the respondents had unrestricted time conditions, the respondents were not pressured with any time windows. Question 4, the *performance*, asks for the individual satisfaction relating the task to be accomplished, or how successful the respondents think they were while completing the task and to reach the goal. While the majority of respondents agreed to have reached the goal of the task well, there are positive effects present between especially PC_rD_+ and PC_fD_- to PC_rD_- and to PC_fD_+. Considering Table 10.15, the effect of PC_fD_- to PC_rD_- is small for *performance* but present.

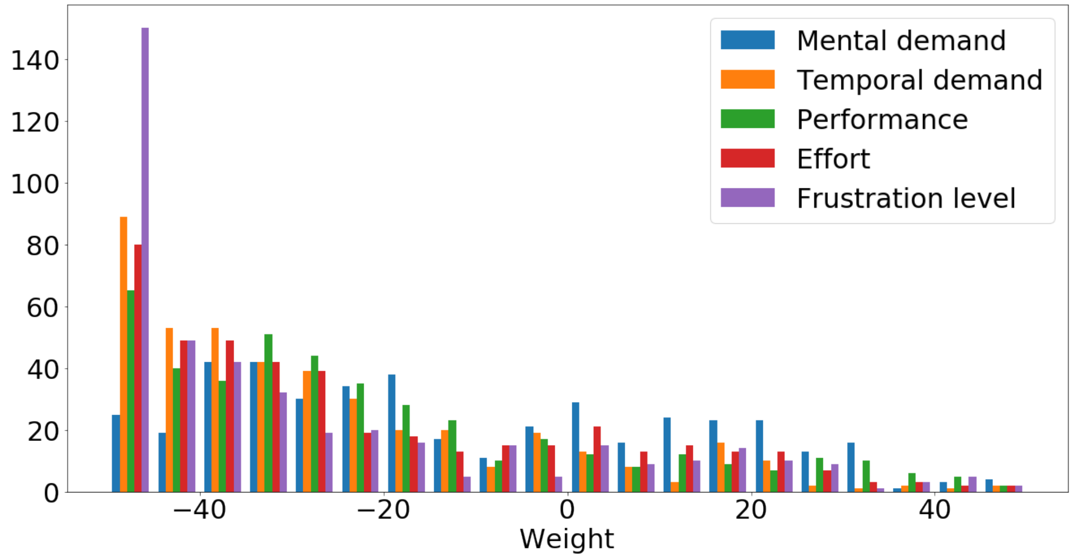

FIGURE 10.15: Distribution of the respondents' answers to the NASA TASK LOAD INDEX (TLX) questionnaire

This treatment is statistical significant by a statistical U-test (T-test) with one asterisks (*) at -0.027 (-0.037). That means that using the reduced design of PC without the presence of a bar diagram, although the effect is small, the samples differ with a statistical significance and the reduced design leads to a higher satisfaction with someone's goal achievement or results in a higher confidence that the goal was rather reached. A further statistical significance was detected at $\text{PC}_r D_-$ to $\text{PC}_r D_+$, the presence of a bar diagram differ the samples sufficiently with respect to the question *performance*. Due to the effect is negative, $\text{PC}_r D_+$ reduces the own satisfaction achieving the goal, compared with $\text{PC}_r D_-$.

Comparing question 5, the *effort*, and question 6, the *Frustration level*, between the corresponding groups neither show statistical significance nor any noticeable effects. Considering the histogram in Figure 10.15 reveals the distribution across *all* respondents, independent of their group. The histogram explains, without mentioning *physical demand* explicitly, a right-skewed distribution. Therefore, it can be assumed that the overall workload was less for all respondents. Taking especially the distribution of *mental demand* into account, the weights are above others in general, whilst the mean is more right. This observation is consistent to the observation described beforehand.

Besides this, complexity might affect the consistency of a PC matrix, as described in Section 3.1.3. The consistency ratio of a PC matrix expresses the standardized degree of consistency among the judged criteria. The lower the index, the more consistent is the PC matrix. By design, the reduced design of PC make inconsistencies impossible since the asked pairs are too less and the PC matrix is completed in such a way that no consistencies are built. In contrast to the reduced design, the full PC

Question	Baseline	Treatment	Simple Effect	Effect size (d)	U-test	T-test
Mental demand	PC_fD_-	PC_rD_-	-2.072	-0.085	0.505	0.529
	PC_fD_+	PC_rD_+	-2.755	-0.111	0.288	0.425
	PC_fD_-	PC_fD_+	-0.832	-0.034	0.852	0.803
	PC_rD_-	PC_rD_+	-1.515	-0.060	0.572	0.657
Physical demand	PC_fD_-	PC_rD_-	1.441	0.105	0.95	0.435
	PC_fD_+	PC_rD_+	0.837	0.080	0.525	0.564
	PC_fD_-	PC_fD_+	-1.704	-0.155	0.33	0.261
	PC_rD_-	PC_rD_+	-2.309	-0.173	0.668	0.203
Temporal demand	PC_fD_-	PC_rD_-	-1.532	-0.073	0.469	0.587
	PC_fD_+	PC_rD_+	-1.801	-0.083	0.573	0.55
	PC_fD_-	PC_fD_+	1.017	0.047	0.922	0.733
	PC_rD_-	PC_rD_+	0.748	0.036	0.767	0.793
Performance	PC_fD_-	PC_rD_-	-6.577	-0.282	0.027 *	0.037 *
	PC_fD_+	PC_rD_+	4.082	0.165	0.357	0.236
	PC_fD_-	PC_fD_+	-3.372	-0.141	0.32	0.304
	PC_rD_-	PC_rD_+	7.287	0.301	0.044 *	0.027 *
Effort	PC_fD_-	PC_rD_-	-0.315	-0.012	0.916	0.926
	PC_fD_+	PC_rD_+	0.365	0.016	0.641	0.906
	PC_fD_-	PC_fD_+	-3.210	-0.139	0.704	0.31
	PC_rD_-	PC_rD_+	-2.530	-0.102	0.51	0.45
Frustration level	PC_fD_-	PC_rD_-	-3.964	-0.162	0.478	0.229
	PC_fD_+	PC_rD_+	3.580	0.143	0.834	0.301
	PC_fD_-	PC_fD_+	-3.374	-0.141	0.763	0.307
	PC_rD_-	PC_rD_+	4.170	0.164	0.499	0.226

TABLE 10.15: Effect sizes of the NASA TASK LOAD INDEX (TLX) questionnaire across the groups PC_fD_-, PC_fD_+, PC_rD_-, PC_rD_+

offers the possibility to create inconsistencies. This information given, only the samples PC_fD_- and PC_fD_+ need to be considered.

Figure 10.16 shows a histogram where the the distribution of PC_fD_- and PC_fD_+ are shown. As demonstrated, the distributions are very similar to each other. The mean of the consistency ratio of PC_fD_- is $\overline{CR}_{\mathrm{PC}_{fD_-}} = 0.146$, for PC_fD_+ is $\overline{CR}_{\mathrm{PC}_{fD_+}} = 0.146$, too (combining both samples, the consistency ratio of PC_f is $\overline{\mathrm{PC}_f} = 0.146$). To support this observation, the result of a statistical U-test reaches a p-value of 0.996 for PC_fD_- versus PC_fD_+ with a negligible standardized effect of -0.001.

Considering Figure 10.17, the scatter plot shows the correlation between the FCHR of the full design PC_f against the consistency ratio of the PC matrix of the PC_f (since the consistency ratio of the PC matrices is always 0 at PC_r). The Pearson correlation coefficient is at -0.245, i.e., a decrease of the consistency ratio leads to an increase of the FCHR. Beyond this regression line shown in Figure 10.17, the coefficient of determination is $R^2 = 0.077$. This examination follows the assumption that the more consistent the PC matrix is (indicated by the consistency ratio of a given PC matrix), the better the FCHR reached by PC. Since no effects were determined

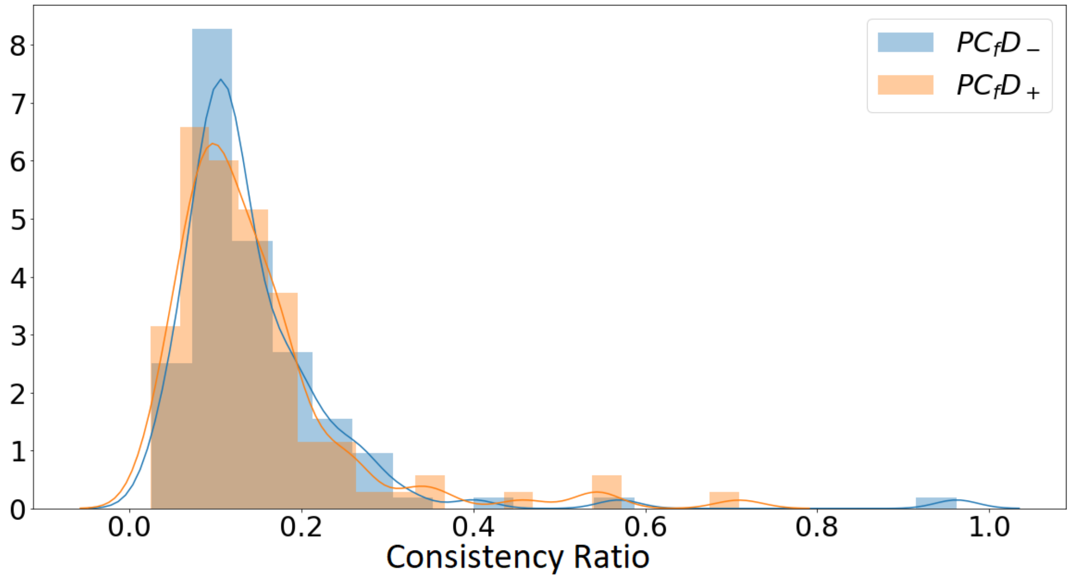

FIGURE 10.16: Distribution of the consistency ratio among PC_fD_- and PC_fD_+

	Group	*FHCR*	Duration *PC*	*CI*	Mental demand
Group	0	0.0066	0	0	0.3295
FHCR	0.0066	0	0.88	0.6266	0.971
Duration *PC*	0	0.88	0	0	0.0173
CI	0	0.6266	0	0	0.1962
Mental demand	0.3295	0.971	0.0173	0.1962	0

TABLE 10.16: P-Values between further endogenous variables

when a bar diagram is used, as shown in Figure 10.16, the scatter plot in Figure 10.17 needs not to distinguish between both.

The following remarks are also related to complexity and the time required to complete the tasks, depending on the group by which the task were completed. By just considering the FCHR of group PC_f as endogenous variable, the explained variance, determined by a multiple linear regression, of the consistency ratio is given at $R^2 = 0.060$. Although this R^2 is not quite high, it is the third highest among all features in this group with respect to this endogenous variable FCHR. Just the Pearson and Spearmann correlation coefficient between the derived weights of the PC and the CA are above. The time required for the PC tasks also explained the variance better than the remaining other features, i.e. $R^2 = 0.015$. This observation supports the analysis so far and depicts that the duration of the PC task and the consistency ratio of the PC matrix are related to each other.

A next impression is given in Table 10.16 in which further endogenous variables with their corresponding p-values are shown.

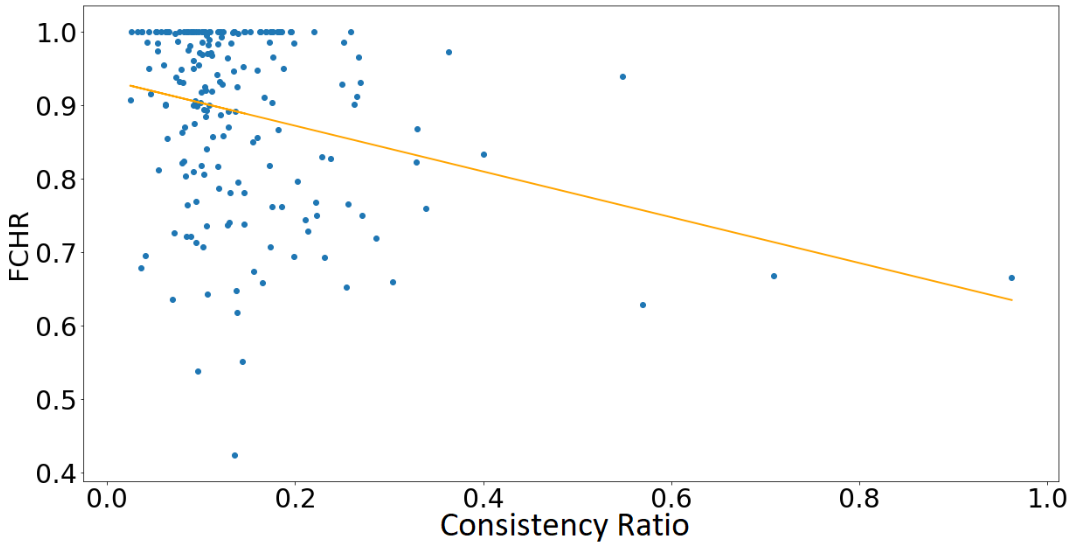

FIGURE 10.17: Correlation between the First Choice Hit Rate (FCHR) and PC matrix consistency ratio (CR) of PC_f

10.6 Conclusion

In this experiment, the accuracy rate of PC in a reduced design and a full design, in each case without and with a bar diagram as visual support, were compared and benchmarked against a classic CA. The experiment had taken place on February 7, 2020 and had recruited 438 respondents in the duration of around 45 hours. The main research objective was to examine differences between the full design of PC as baseline and a treatment where a reduced design of PC is used, mainly based on Koczkodaj and Szybowski (2015b).

10.6.1 Summary

This section summarizes the results of the experiment and interrelates the results with the introduced research hypotheses. For this purpose, Table 10.17 embraces all introduced research questions and their corresponding hypotheses of Section 10.3 and the derived overall verdict with respect to the result, whether an alternative hypothesis is to be supported or rejected, given the results of the experiment.

The first assertion belongs to research question 6, whether an effect is given in the difference between the full or the reduced design of PC. The verdict here is *mostly supported* since more of the samples examined have revealed a difference with a statistical significance between the full and the reduced design of PC. The FCHR has shown that, for the merged groups PC_f versus PC_r, there is a p-value of 0.029. Because the effect seems not to be caused by the treatment with the bar diagram present D_+, the difference can be reduced to the kind of preference measurement, that is the reduced over the full design of PC. Either way, the statistical significance diminishes slightly when a bar diagram is present D_+, then the p-value is 0.041.

RQ	Assertion	Verdict
6	There is a difference in accuracy between the reduced and full design of PC.	mostly supported
6	There is a difference in cognitive (work-)load between the reduced and the full design of PC.	partly supported
6	There is a difference in accuracy between the PC reduced and the CA.	partly supported
7	There is a difference in accuracy when using a bar diagram combined with the PC.	not supported

TABLE 10.17: Results of the hypotheses

Consequently, the assertion is generally supported that the reduced design of PC differs from the full design of PC, even if a bar diagram is present D_+. The accounted standardized effect is *small*, i.e. the reduced design of PC is worse compared to the full design of PC. A further impression can be drawn back to small differences between the effects, i.e., the effect of PC_f compared to PC_r is smaller than the effect between $\text{PC}_f D_+$ compared to $\text{PC}_r D_+$, whilst both a generally small by definition. The p-value of the corresponding U-tests is contrary here, since it is higher at $\text{PC}_f D_+$ compared to $\text{PC}_r D_+$ than the U-test at PC_f compared to PC_r. Howsoever, the effect is small and the time savings high, meaning that the reduced design of PC takes so much less time compared to the full design of PC. Additionally, as explained in Section 3.1.3, the Consistency Ratio (CR) should be less than 0.1, which was not observed in the experiment for the PC_f (the reduced design of PC is not considered so far, since it is consistent by design). The averaged consistency ratio for PC_f is 0.146 while it is quite stable across $\text{PC}_f D_-$ and $\text{PC}_f D_+$. With these observations in mind, the PC matrices need further adjustments to get sufficiently consistent. In such a case, it seems advisable to take advantage of procedures where consistency is given by design. Especially with Figure 10.17 indicates that the more consistent a decision matrix, the more accurate the FCHR.

Considering the second hypothesis, which belongs also to research question 6, it is accounted whether an effect or statistical significance was observed when using a reduced design of PC, compared to using a full design of PC. The verdict is here *partly supported*. The respondents were asked to self-explain their (work-)load while processing the PC, that is either $\text{PC}_f D_-$, $\text{PC}_f D_+$, $\text{PC}_r D_-$, or $\text{PC}_r D_+$. Generally, no statistical significances were observed, except for the question *performance*. Performance means, as described in Table A.2, of how successful the respondents think they had accomplished the goals of the task set by the experimenter. And, furthermore, how far they are satisfied with their performance in accomplishing these goals. According to the observations, given the baseline $\text{PC}_f D_-$ in comparison to the treatment $\text{PC}_r D_-$, there was an effect accounted at -0.282 (low effect) with a statistical significance of 0.027, i.e., the satisfaction with their performance was slightly better when using the reduced design of PC. It could be that respondents are more likely rely on the result of the reduced design of PC and, in turn, a reduced design of PC might increase the trust in the preference elicited. Further analysis disclosed that the presence of a bar diagram decreases the performance when the reduced design of PC is used. The standardized effect size is 0.301 at a statistical significance of 0.044, i.e., the respondents self-explained a slightly worse performance. Based on these observations, a bar diagram showing the relative importances of the criteria weights might bring confusion about the perceived certainty or could causing misleading interpretations.

The last and third hypothesis of research question 6 aims at the assertion that a difference in accuracy between the PC and a classic CA is given. Again, with accuracy, the accuracy rate is meant and operationalized to FCHR. The CA was used as benchmark and was proved to be sufficient, since its performance (also operationalized to FCHR) holds stable across the both groups. The CA is an established method in marketing to quantify user preferences. In the experiment, the CA was used in two ways, i.e., both to examine the correlation on the level of weights of criteria and to examine the CA and the PC as estimators by means of the FCHR. First, the Pearson correlation between the CA and the PC on the level of criteria weights was examined. The overall observation was that all Pearson correlation coefficients were positive, meaning that the criteria weights of CA are growing with the PC weights. For $\mathrm{PC}_f D_-$ versus $\mathrm{PC}_r D_-$, there was with -0.239 a small negative standardized effect observed, i.e., the the Pearson correlation coefficient is reduced when using the reduced design of PC, but less confident due to a p-value at 0.13. Beyond this, a high statistical significance (***) is given with 0.001 at the standardized effect of -0.469 (almost medium) at $\mathrm{PC}_f D_+$ versus $\mathrm{PC}_r D_+$. That is, when a bar diagram is present, the statistical significance becomes important and the standardized effect is increased in the negative direction (a similar observation is given for PC_f to PC_r with a statistical significance at 0.001 and a standardized effect of -0.344). This observations given, the correlation between the criteria weights is worse when using the reduced design, and the effect gets stronger and even significant, when a bar diagram is used.

The FCHR is calculated by means of the PC and the CA. Further conclusions are therefore derived from observations of the FCHR between the PC and the CA. It can not be surely explained that the PC is better or worse compared to the CA, as the PC_f performs better with statistical significance while PC_r performs worse, but without statistical significance and a very small (standardized) effect. These observations are compatible to the afore-mentioned findings. The statistical significance was observed at D_+, $\mathrm{PC}_f D_+$, and PC_f, meaning that especially the presence of a bar diagram together with the full design of PC seems to increase the performance over CA. Further analyses show that, in general, the better the FCHR of CA, the better the FCHR of PC, indicated by Figure 10.12.

In view of the first hypothesis of research question 7, the assertion was to examine whether a bar diagram causes a change in the accuracy, represented by the

FCHR, when using in PC. For this examination, there were dedicated samples collected, namely D_- and D_+. Both samples were combined with the main research object, the full PC_f versus reduced PC_r design of PC. A statistical significance with respect to the accounted effects where a bar diagram was treated D_+ was never observed. However, the diagram seems causing an indirect effect to $\text{PC}_f D_+$ versus $\text{PC}_r D_+$, where the effect is accounted with statistical significance if and only if a bar diagram is present. While $\text{PC}_f D_-$ versus $\text{PC}_f D_+$ already indicated a slightly worse effect, the effect is worse on $\text{PC}_f D_+$ versus $\text{PC}_r D_+$. Moreover, the effect becomes statistical significant, reducing the randomness or arbitrariness in the occurrence of the effect and the effect comes more reliable. Since the effect could not be measured directly, nevertheless, it remains an open question where the effect finally and completely comes from.

10.6.2 Discussion and Further Research

Altogether, this research was motivated by the large number of pairs required to be judged in PC and the drawbacks emerging out of this. This research used a completion algorithm to complete a PC matrix for the AHP as the result of a reduced design of PC, when the criteria pairs are pre-determined in a specific way. The main research objective was to compare performance of the reduced design of PC to the classic and full design of PC in a experimental way. Beyond this, it was examined how far a bar diagram showing the current criteria weights during the PC can help in the judgement phase to, e.g., avoid inconsistencies in the PC matrix. The results show that the reduced design of PC differs with statistical significance from the full design of PC. Since the effect is small, decision makers, survey designers, or other users of PC or AHP need to consider the advantages, such as time savings, a fully consistent decision matrix, the option to increase the number of criteria to tackle complex use cases possibly better, and to tradeoff those advantages against the small effect in loss of accuracy.

The experimental results disclose that there is no statistical significance between PC with or without a bar diagram in general. When diving more into details, the diagram seems to play a specific role since a small but statistical significant effect occurs. Because the causality of the effect could not finally be described by the statistical analysis of the experiment, further research might focus on the precise causality of this effect occurring when a bar diagram is used as visual support.

Additionally, in this experiment the original Saaty's scale of PC of the AHP where used. It might be worth considering to evaluate another scale for the PC by which the completion algorithm would not produce such noticeable small or big values for the auto-completed criteria weighs. Since the derived values are reached by multiplication due to the consistency condition, smaller values should result when reducing this original scale down. On the basis of a changed scale, additional experiments might be conducted or the given experiment's data might be used to optimize the used scale until the accuracy between the PC judgement and respondents' choices are maximized.

Part V

Finale

Chapter 11

Conclusion & Future Work

> The shape and solutions of the future rely totally on the collective effort of people working together. We are all an integral part of the web of life.
>
> Jacque Fresco

11.1 Summary and Contributions

The world grows together. Globalization does not stop on borders and affects almost any realm. Digital transformation and new technologies accelerate these changes and leave marks on the society. Much of this growth is based on the utilization and exploitation of natural resources, provisioned by common goods. These natural resources need to be managed in a more sustainable way, before developments with negative externalities turn out to continue inevitably.

Despite the majority concede that something have to change, the society fails to prevent the nature from further deconstruction and overuse so far. Rather more, the problem draws back to societal conflicts, securing interests, national borders, perceived inequality - to mention some. To overcome these problems, entirely approaches are required, which yield the best decision for the society as a whole, without deteriorating the final outcome due to individual interests.

The work at hand assumes the final outcome to be optimal once social welfare is maximized, and proposed participatory decision-making among individual rational participants to reach it. With the condition of individual rationality, a more pessimistic than an optimistic assumption about the behavior of participants is made: participants are then assumed to act completely according to their utility-increasing functions. Apart from that, individual rationality is faced by group individuality, between which sometimes are contradictions. The well-known prisoner's dilemma exemplifies this on a concrete game-theoretical situation, and the collective action problem - also known as social dilemma - generalizes this in such a way to be compatible to many use cases of our daily life, in particular to those common goods being in question. The overall question approached in this work at hand is how to deal with these decision situations.

New technologies being invented by so-called Distributed Ledger Technology (DLT) promise to connect such selfish participants together to reach shared goals. With contemporary developments such as blockchain 3.0, token economy, and smart contracts, the range of potentials is additionally extended. Some applications were undertaken with respect to decision-making, especially elections or votes – DLT-based governance research attracted attention in the last years. Based on this, Section 1.2 introduces the following research questions in the same order, which are linked with their corresponding contributions to the superior research endeavor. The first insight states that DLT together with participatory decision-making in the field of common goods was not yet examined, which was examined by the following research question:

> **Research Question 1:** *How is the Distributed Ledger Technology (DLT) used in the field of bioeconomy?*

As a result, **contribution 1** is given on the basis of research question 1. A systematic literature review about the usages of DLT in the field of bioeconomy is given. This contribution is based on a literature review that follows the guidance of Brocke et al. (2009) and Webster and Watson (2002). The focus of the literature review is to find related practices and/or applications where DLTs and bioeconomy were discussed. Because the combination of bioeconomy / DLT was not widely discussed, central issues within this intersection are identified. Given these findings, the today's applications of DLTs cover more and more use cases. Energy internet is one big topic in this area. In accordance with the derived research agenda, further applications address governance, on-chain votes / elections, but also interorganizational cooperation, or connecting participants in order to achieve a shared goal, for instance a societal desired outcome. Especially the token economy promises new pathways for further research in this field. Different kinds of tokens depict several assets. Physical assets such as real estates can be depicted and their price is determined by market mechanisms. Fungible (identity-dependent) and non-fungible (identity-independent) tokens depict securitized promises such as access rights. With developments around blockchain 3.0, smart contracts, or token economy, completely new potentials emerge. This insights given and according to reserach question 2, a first draft of a Participatory Decision-Making System (PDMS) is elaborated.

> **Research Question 2:** *What does a Participatory Decision-Making System (PDMS), conceptualized by Distributed Ledger Technology (DLT), look like?*

That way, **contribution 2** refers to a conceptualized PDMS, which is derived by requirements elicited along a forest use case, being illustrated by the current forest situation in Germany. The conceptualized PDMS can be understood as an instantiation fulfilling the outlined requirements with focus on participation. It is the first conceptualized description of a PDMS for a participatory forest management use case. The conceptualization follows a business process created by means of Business Process Model and Notation (BPMN), which introduces a complete life cycle process from starting, over running, until stopping an on-chain PDMS. Moreover, as more and more applications of DLT arise, the more critical do researchers and practitioners observe this propensity, resulting in a skeptical environment with uncertainties and a special need to justify reasonably, whether a DLT makes sense or not – following this, the contribution explains step-by-step why DLT makes sense and interconnects the elicited requirements with the DLT-related solutions. At the end, future potentials and DLT-related open questions are given. Based on contribution 2, a DLT-based PDMS is sketched, but without mentioning which DLT can be used for such a PDMS.

> **Research Question 3:** *Taking a Participatory Decision-Making System (PDMS) into account – what is the best suited Distributed Ledger Technology (DLT) with highest utility for that use case?*

This opened further research gap is filled by **contribution 3**. A general framework on the basis of MCDA, and more precisely AHP, is used to create a decision model for a DLT selection problem. The identification of decision criteria and DLT alternatives follows a systematic elicitation approach. The decision criteria were judged against the DLT alternatives, which are analyzed by a Monte Carlo simulation – irrespective of any specific use case. This gives an overview about the probability to reach each DLT alternative on the level of different ranks. This makes the decision model more general to other use cases, increases the decision certainty of DMs, and shows the application breadth of the DLT alternatives. The decision model is exemplified specifically for the PDMS, but is not limited to this. For the application to other use cases, there is just a specification of the preferences on the level of criteria necessary. For the PDMS use case, Ethereum as DLT is recommended, and the result is analyzed with a sensitivity analysis to show the robustness of the DLT recommendation. This sensitivity analysis, together with the relative distribution to reach the corresponding DLT alternatives, increases the decision certainty for the recommendation of the DLT alternative to the use case PDMS. An academic implication is that, for the first time, the AHP is used with a reduced design (Koczkodaj and Szybowski, 2015a) of PC and that a Monte Carlo simulation is applied. The practical application is that a general decision model for the DLT selection problem is proposed and applied in particular for the PDMS use case. With contributions 2 and 3 in mind, a further question is how a PDMS should be designed to reach best decisions (which maximizes social welfare) for all participants together.

> **Research Question 4:** *How to incentivize truth-telling in participatory multiple-criteria decision-making over management alternatives of a common good?*

Contribution 4 clarifies how a PDMS can be meaningful designed and how it looks like once it is instantiated by a DLT. For this purpose, mechanism design as superior procedure to elicit and aggregate preferences is used. This contribution combines the public good game with MCDA, which allows the participants to determine their optimal decision. This intersection, including a social choice function determining an alternative of a set of alternatives, is the main academic implication. MCDA itself is a proven methodology for decision-making for common goods (such as the forest) and was applied participatory. Therefore, the well-known public good game (also known as public project problem) is extended to be compatible with MCDA. This theoretical contribution illustrates how selfish agents can determine their optimal alternative in a multi-criteria public good setting (and how a MCDA-compatible social choice function looks like), in order to determine a pareto-efficient outcome at the end. The calculation schema belongs to the VCG family and, thus, makes it a weakly-dominant strategy for the participating agents to report truthfully their preferences. Finally, this contribution is evaluated by an agent-based simulation and exemplifies its applicability through a forest management use case.

As the DLT itself follows a completely decentralized approach and assumes selfish participants to be involved in, the same selfish-assumed participants decide the management of a common good in a participatory way. Mechanism design is a discipline that allows system operators (e.g. potential designers of a PDMS) to design a system to reach a predefined goal. This goal is the pareto-efficient provision of an MCDA-based alternative that maximizes the social welfare among the participants.

> **Research Question 5:** *To what extent does a Participatory Decision-Making System (PDMS) give utility to whom and does the Distributed Ledger Technology (DLT) add value in participation?*

Participation can be divided to ordinal-scaled categories (inform, consult, involve, collaborate, empower) (IAP2, 2014), allowing to express someone's desired level of participation impact. DLT, on the other side, is able to coordinate decentralized decision-making to the extent of a PDMS, and has DLT-specific features since it works consensus-driven (decentralized power), transparent, immutably, and decentralized – where it is hypothesized that the utility of the afore-mentioned participation impacts can be further increased. That way, **contribution 5** states an added-value resulting from the DLT-specific features. These results are achieved by an online survey and a face-to-face survey with the same questionnaire and a total number of 102 respondents. The DLT-features, which let the DLT be transparent, consensus-driven, immutable, and decentralized, maximize the utility for those with a high willingness to collaborate. For those with a willingness to participate on the level of inform, the preferred DLT alternative differs from decentralized power to concentrated power at the DLT-feature consensus-orientation.

When it comes to decision-making itself, AHP in the field of MCDA is a well-known means, especially with respect to infrastructural projects or common goods. MCDA's idea is to allow decision makers to determine their optimal decision alternative among a discrete set of alternatives. Game theory and mechanism design does not only suppose rational and selfish agents to be given, they also assume that agents are *intelligent* and *able* to determine their best alternative (strategy or type in a game-theoretical sense). Therefore, to increase the ability to self-determine someone's own preferred alternative, an experimental analysis examines a reduced design, compared to a full design of AHP. PC allows decision makers to judge relatively between decision criteria, which is an advantage against fix point weighting methods such as likert scale, point allocation, rating scales, and so forth. However, since PC allows inconsistencies between judged criteria and tends to a huge growth in pairs to be compared, it is hypothesized that a reduced design outperforms a full design of PC, embedded in the AHP.

> **Research Question 6:** *A reduced design of Pairwise Comparison (PC) integrated in the Analytic Hierarchy Process (AHP): Is it better or equal to the full design?*
>
> > **Research Question 6.1:** *Does the reduced design of Pairwise Comparison (PC) change the cognitive load during the judgement phase?*
> >
> > **Research Question 6.2:** *Does the reduced design of Pairwise Comparison (PC) lead to different results compared to a classic Conjoint Analysis (CA)?*

Considering **Contribution 6**, a reduced design by Koczkodaj and Szybowski (2015b) is compared to a full design – as design by Saaty (1980) – of PC, both embedded in the AHP. For this purpose, 438 respondents were invited and had participated in an online experiment. The results show that the reduced design of PC is slightly worse than the full design (with statistical significance). Since the deterioration is at a small level – operationalized to a small accounted effect size –, decision makers need to tradeoff the advantages of a reduced design, such as time savings, a fully consistent decision matrix, the possibility to tackle more complex use cases better due to the potential to include more criteria, against the small effect in loss of accuracy. The subordinated **contribution 6.1** is about the cognitive load during the judgment phase. It is hypothesized that, for the reduced design, the cognitive load is smaller due to the reduced number of pair judgments including the time savings. Results show that this alternative hypothesis could not be accepted; however, when using the reduced design, the own's confidence is higher and the satisfaction with the results increases compared to the full design – on the basis of this last mentioned observation, it can be said that the reduced design might obtain more acceptance than the full design. **Contribution 6.2** states, in accordance with contribution 6, that a classic Conjoint Analysis (CA) outperforms the reduced design while the full design outperforms the classic CA. These results have no statistical significance, however, the results of the CA are stable (with very similar results) across these two groups (reduced and full design), indicating the CA to be a sufficient benchmark, such that the reduced and the full design can additionally compared among themselves (that way, the CA can be understood as a stable alternative way to derive preferences and to depict a point of reference for these derived preferences). Finally, the core contribution here is that the reduced design has a very small loss in accuracy, but gains in time savings (due to the reduced number of comparisons required) and consistency between the criteria judgments, what it makes an economic decision which one to choose.

> **Research Question 7:** *Does a bar diagram affect the performance when displaying the relative importances of the criteria during the Pairwise Comparison (PC) phase?*

The **contribution 7** is strongly related to the contribution 6 (including 6.1. and 6.2), and examines a visualization to display the current criteria weights during the process of PC. Due to the high number of comparisons required, the decision maker could lose control or overview while deciding. Further, the more the comparisons require time, the more the task challenges the decision maker cognitively. It is thus hypothesized that a visualization in form of a bar diagram helps the decision maker to judge the criteria – resulting in a more consistent decision matrix and a lower cognitive load. Results indicate that a bar diagram increases the accuracy of the full design of PC, but not with a statistical significance. However, when using the reduced design of PC, the diagram increases the time required and decreases the own‘s satisfaction. Moreover, it does not lead to more consistencies in the full design of PC.

Altogether, contribution 1 works out general research directions in the field of DLT and bioeconomy, creating the basis for engineering contributions 2 and 4 that are built substantially upon that. With contribution 2, a general business process for a PDMS is derived in a requirement-driven manner, including the DLT as underlying technology. Following this, contribution 4 shows – by means of mechanism design approach – how a PDMS can be designed in order to reach efficient outcomes in the field of participatory decision-making in a multi-criteria environment (as usually in forest management). Furthermore, contribution 3 clarifies which DLT is recommended to use in combination with the introduced PDMS. When it comes to participation in the field of forestry, contribution 5 gives information about the desired configuration of a DLT on the level of different participation impacts, and concludes that an immutable, decentralized, transparent, and power-distributed approach is preferred on the level of collaboration as preferred participation impact. With respect to contribution 4, mechanism design is used and rational and *intelligent* participants are assumed. These *intelligent* participants should be able to find their optimal response in a participatory decision-making problem. Therefore, the weighting method PC – embedded in the AHP as well-known and established decision-making method in the field of forestry – is examined. Contribution 6 shows that decision-makers can use a reduced design of PC in the AHP, with a small loss in accuracy, while being able to use more complex use cases with an increased number of criteria. At the end, it results in an economical decision to use the full or reduced design of PC. Considering contribution 7, using a bar diagram as visualization does not lead to more consistencies in the full design of PC, and increases the time required for the judgment phase.

11.2 Future Work

The work at hand opens several pathways for further research. These potential future works embrace, beside others, research directions aligned to DLT, game theory, behavioral experiments, and MCDA – or combination of these. They are mainly based on the contributions that are outlined before.

How the Distributed Ledger Technology Revolutionizes the Society and Economy

Research and development around DLT continues. After blockchain 1.0 and blockchain 2.0, nowadays discussion covers topics around bockchain 3.0. While blockchain 1.0 was mainly based on the transfer of money, that is cryptocurrencies, its wide emergence was extensively grounded on Bitcoin. Next, blockchain 2.0 introduced a next generation of DLT, which was widely driven by the invention of smart contracts. Smart contracts, in turn, make developments such as Decentralized apps (so-called Dapps) and Decentralized Autonomous Organizations (DAOs) possible. With smart contract implementations, the so far existing financial transfers are extended to behave (to be executabe) depending on user-defined events such as time or other conditions. This developments are generally not limited to the financial area, but are especially applicable to other use cases such as electronic voting (e-voting), healthcare records management, identity management systems, access control systems, decentralized notary (with a focus on intellectual property protection) or supply chain management (Maesa and Mori, 2020). These extensions and this broader coverage of use cases lead to the development blockchain 3.0.

These developments have also causes and implications along the *new institutional economics*. In this sense, the DLT might reduce transaction costs emerging when participants are trading in a market (Coase, 1995). Among others, transaction costs are determined by uncertainties (Williamson and Masten, 1999), which are affected by smart contracts that make trading more binding because they are executed automatically and according to predefined rules. Further, uncertainties are encountered by the transparency that is inherently provided with the DLT. Consequently, both the ex-ante costs such as information retrieval are reduced due to its transparency and traceability, and the ex-post costs are reduced due to its reliability and its kind of automatic execution.

Because contributions of this work are connected to e-voting, open questions in particular this field can be highlighted. This and other use cases attract more and more attention while the so-called token economy emerges. While e-voting could lead to an increase of turnouts, further research should focus on feasibility of time savings or less mobility requirements, and therefore how burden to cast votes really can be reduced. The more often votes happen, the higher burdens of classic voting, such that e-voting might outweigh these drawbacks. Such research efforts includes technology acceptance examinations as well, and the (or simply the perceived) risk of tampering and further security concerns, too. E-voting, based on DLT, might look more complicated due to, for example, public key cryptography. A further preferred requirement to fulfill is ensuring that the DLT e-voting system itself guarantees both integrity and anonymity of voters. This point is due to the vote secrecy property. In turn, it is desirable that only these people can vote that are eligible to vote. This also includes, for instance and if desired, that people should not be able to vote twice. Another topic worth researching is about the price of a fee of transactions, for instance, on Ethereum. As outlined by Maesa and Mori (2020), the DLT-based e-voting system described by McCorry, Shahandashti, and Hao (2017) processes votes with a linear growth of fee in the number of voters. Due to such constraints, the today's maximal amount of votes for a tallying process is at 100 voters per Ethereum block. These circumstances make adoption more difficult and increases the need for research to make DLT more efficient. Some of these endeavors are also covered by the movement around and are part of the next generation of blockchain 3.0. When discussing about collective decisions running on the DLT, a further recent innovation is made by Wright Jr (2019), who invents quadratic voting. Quadratic voting allows participants not just to express to be in favor or to be opposed to something, but it allows participants to express their degree of being in favor or being opposed to something. Quadratic voting makes this possible by offering the opportunity to vote multiple times, while the cost per vote growth in a quadratic way. Considering this development, questions are how quadratic voting might be integrated in a fair manner and without to foster inequality due to less wealth of some few people. It is worth considering how MCDA could be connected to quadratic voting in order to elaborate an alternative to the approach proposed in this work. Consequently, quadratic voting can be understood as a simple alternative to express the willingness to pay for the given alternatives. However, when quadratic voting is used as measure to derive a willingness to pay, the game-theoretical implications must be considered.

Purpose-Driven Tokens

A further invention that is closely linked to the token economy are the so-called purpose-driven tokens. Purpose-driven tokens are tokens created, maintained, and offered by a DLT, first and foremost by Ethereum. As mentioned by Voshmgir (2019):

> *"Purpose-driven tokens incentivize individual behavior to contribute to a collective goal. This collective goal might be a public good or the reduction of negative externalities to a common good. Purpose-driven tokens introduce a new form of collective value creation without traditional intermediaries. They provide an alternative to the conventional economic system, that predominantly incentivizes individual value creation in the form of private goods."*

It can be understood as another way to approach the environmental issues. One established way to approach environmental issues is to use compensatory measures (Van Hoorick, 2014). Compensatory measures encounter the problem of negative external effects (externalities) on the environment, caused by consuming goods or services for whose ecological (environmental) costs are not paid. This problem is solved by an internalization of externalities. In theory, the price of products and services internalizes these monetarized externalities. In other words, the logic behind compensatory measures is to internalize environmental costs (the externalities) that are caused by, for instance, air pollution by flying or more shipments due to the increase of e-commerce. Compensatory measures are mainly based on voluntary decisions, thus they are not mandatory. As environmental costs are quantified and internalized into the price of products or services, for example, forest owners are therefore incentivized to do reforestation or to preserve sustainability by supporting the protection function of a forest. Consumers, in turn, are incentivized to re-analyse the offer and to take the environmental costs into consideration. The idea behind purpose-driven tokens is similar, but differs slightly. They intend to incentivize humans to work collectively for a collective goal instead of exclusively pursuing own interests by maximizing one's personal profit. While compensatory measures are voluntary, rational and selfish people will avoid them, purpose-driven tokens set an incentive structure that encourages participants to behave according to the rules. Another drawback is that compensatory measures do not avoid environmental costs as negative externalities, they just intend that they are paid. Purpose-driven tokens, instead, set incentives to avoid their creation in general. The "purpose" is the collective goal, for instance the reduction of CO2 emissions. Instead of compensating self-caused externalities created by consuming goods and services, purpose-driven tokens create collective value by avoiding externalities. In exchange for avoidance of externalities, tokens are emitted to participants – at the end, both approaches associate (monetary) value to ecological costs. It is important to understand that the application fields of purpose-driven tokens is not limited to CO2 emission. Instead, purpose-driven tokens should incentivize the behavior of humans in general, in order to reach collective goals where – expressed in a game-theoretical sense – individual rationality is oftentimes in contradiction to collective rationality.

Open questions are how the participants' behavior can be tracked sufficiently to ensure reliably that the participants really contributed to the collective goal. Questions around data protection laws arise. Further, what is working in theory does not inevitably hold for the real-world behavior of humans, such that behavioral economics as well as nudging research is advisable. Apart from that, behavioral finance and behavioral game theory studies when and why participants do not behave according to the theory of individual rationality, and reacts with theories such as regret theory, hyperbolic discounting, and prospect theory. People might minimize the feeling of regret after they made a decision. Many DLT-based concepts are based on the theory of individual rationality and many rules and the design of systems are defined by game-theoretical mechanism design theory, such as the consensus protocols, token curated registries (TCRs), token bonding curves, or algorithmic stable tokens (Voshmgir, 2019). Nevertheless, these concepts need to be further evaluated on the basis of behavioral economics, and behavioral finance, and behavioral game theory, and cognitive psychology. As already explained by Voshmgir (2019), when it comes to the design of purpose-driven tokens, then purpose-oriented mechanisms are required. An emerging field is the "token engineering". While the two most discussed consensus-mechanisms Proof-of-Work and Proof-of-Stake required a rigorous history of research, this is probably true as well for the design of purpose-oriented mechanisms. For example, there have hardware and software oracles to be examined to bridge the gap between on-chain environments and reality, that is other off-chain systems.

Further Developments on Multi-Criteria Decision Analysis

In this work, participatory decision-making is combined with the afore-mentioned DLT-based e-voting. Participatory decision-making is further realized by a MCDA approach. More precisely, this work uses the AHP as particular method in the field of MCDA. This work embeds a reduced design of PC (Koczkodaj and Szybowski, 2015a) in the AHP and evaluates its performance by an experimental analysis. For this purpose, the original scale of PC, as proposed by Saaty (1977), is used. However, the experimental results show that the performance of the reduced design is slightly worse than the full design of PC. This leads to an open question how different scales behave, when they are used with the reduced design. The reduced design uses – to a certain extent – the transitivity rule by multiplication operators to complete the incomplete PC matrix. The higher values of the scale, the higher the numerical products yield by multiplication and due to transitivity. A lower scale for the PC judgment phase could have potential to overcome these issues because the resulting values are smaller and therefore – possibly – more representative for someone's true degree of preference, but this must be designed conceptually and evaluated by an experimental analysis again. Prior the question whether or not a novel scale would work, is the question how a novel scale could look like. The data resulted of the conducted experiment of Chapter 10 could help here to find in a combinatorial way a scale by which the gap between the reduced and the full design are minimized. Put differently, a combinatorial optimization problem can be designed and solved, where the accuracy is maximized as the scale values are varied.

Adjustments on Mechanisms in a Multi-Criteria Environment

Moreover, as this work pursues DLT-based e-voting approaches for common goods, and extends the well-known public good game (or the public project problem) to be working in a multi-criteria environment, further questions are at the intersection of game theory (mechanism design) and MCDA. For example, the VCG payment rule is used to make it a weakly-dominant strategy for all agents to report truthfully their true willingness to pay. As it is common sense that VCG does not inevitably fulfill the budget balance condition, further research should focus on mechanisms where the budget balance condition can be held. For instance, the dominant-strategy incentive-compatibility (DSIC) condition can be relaxed to a Bayesian incentive-compatibility (BIC), resulting in the possibility to reach budget balance and to avoid additional payments to be required to flow into the system – this relaxation is one way to deal with the so-called Gibbard–Satterthwaite Impossibility theorem. Nevertheless, solutions turn out to be ex-post efficient, but without ex-post individual rationality. A mechanism that leads to this result is called dAGVA mechanism. Until now, the dAGVA mechanism was applied neither to a public good setting, nor to the extended version with a multi-criteria environment as proposed in this work. One possible further research direction is therefore the application of dAGVA to the classic public good game and, in a next step, to the public good game extending a multi-criteria environment for participatory decision-making. Furthermore, such theoretical models should and need be evaluated through experiments to examine the real-wold behavior of so-called agents.

11.3 Summary

In the work at hand, the decision-making focuses on common goods, that are characterized by non-exclusiveness and rivalry. These conditions move common goods into scientific and societal consideration. Due to non-exclusiveness, nobody can be excluded from its usage (or consumption) and the free-rider problem occurs. When the common good can be managed in different ways, participants behave strategically and overestimate or underestimate its individual utility. Due to rivalry, the participants face a scarce resource for whose usage the participant's preferences diverge.

On this basis, this work contributes at the intersection of the fields operations research (especially MCDA), information technology (especially DLT), and decision and game theory (especially mechanism design). The work contributes with a PDMS that brings potentially selfish agents together, who co-decide the provision of a management alternative for a common good. Important conditions such as the allocation efficiency hold, such that an alternative is decided that maximizes the social welfare among the participants. For the participants itself, this work contributes to participatory decision-making in a multi-criteria environment.

To reach these contributions, the work at hand starts with a look into the literature to review the state-of-the-art of DLT in the field of natural resources. Research about the design of a DLT-based PDMS contributes a first impression how such an e-voting approach could look like in the field of forestry. On the basis of this contribution, several DLT alternatives are examined and Ethereum as DLT alternative is recommended for that PDMS in the forestry. Since MCDA is frequently used in forest decision-making, it is combined with the public good game, which describes the situation of selfish participants deciding over a common good (probably at best). The AHP, positioned in the field of MCDA, itself is extend and evaluated in an experimental way to support decision-making with various (and an increasing number of) criteria. Finally, a survey gives insights which degree of participation impact and which configuration of a DLT is desired in the field of forestry.

It is common sense that the way to use natural resources must change, requiring new strategies to apply. Those strategies can then be used to manage common goods that offer these natural resources. To ensure that natural resources are used in a sustainable way and to preserve them for further generations, all representatives of the society must be included – with their true needs and preferences. That way, this work contributes with examined insights on how these gaps can be more closed and shed light on further research pathways, to walk towards a better future.

Appendix A

Appendix

A.1 Questionnaires

A.1.1 NASA TASK LOAD INDEX (TLX)

The following questionnaire is known as *NASA TASK LOAD INDEX (TLX)* and was published first by Hart, 1986 and extended by Hart, 2006. Table A.1 shows the questions translated to German and Table A.2 shows the original version in English.

Both tables are structured equally and consists of a identification number, the question title, the question description, and the interval the respondents can weight / choose into. Beyond this, the last column *Interval* contains just the corners of the interval. The respondents see an interval reaching from $-10, \ldots, 0, \ldots, +10$, where -10 belongs to the value at the left side / left of the comma, whilst $+10$ belongs to the value at the right side / right of the comma. Therefore, each question has ten options left and ten options right with the further option to express indifference 0. The more left the respondents chose to put the weight, the more they tend to chose the value left of the comma.

Id	Question title	Question description	Interval
1	Geistige Anforderungen	Wie viel geistige Anstrengung war bei der Informationsaufnahme und -verarbeitung erforderlich (z.B. denken, entscheiden, rechnen, erinnern, hinsehen, suchen etc.)? War die Aufgabe leicht oder anspruchsvoll, einfach oder komplex, war sie fehlertolerant oder erforderte sie hohe Genauigkeit?	gering,hoch
2	Körperliche Anforderungen	Wie viel körperliche Aktivität war erforderlich (z.B. ziehen, drücken, drehen, steuern, aktivieren,...)? War die Aufgabe leicht / einfach / erholsam oder schwer / anstrengend / mühselig?	gering,hoch
3	Zeitliche Anforderungen	Wie viel Zeitdruck empfanden Sie hinsichtlich der Häufigkeit oder dem Takt, mit dem Aufgaben oder Aufgabenelemente auftraten? War die Abfolge langsam / geruhsam oder schnell / hektisch?	gering,hoch
4	Leistung	Wie erfolgreich haben Sie Ihrer Meinung nach die vom Versuchsleiter (oder Ihnen selbst) gesetzten Ziele erreicht? Wie zufrieden waren Sie mit Ihrer Leistung bei der Verfolgung dieser Ziele?	gut,schlecht
5	Anstrengung	Wie hart mussten sie arbeiten, um Ihren Grad an Aufgabenerfüllung zu erreichen?	gering,hoch
6	Frustration	Wie unsicher, entmutigt, irritiert, gestresst und verärgert (versus sicher, bestätigt, zufrieden, entspannt und zufrieden mit sich selbst) fühlten Sie sich während der Aufgabe?	gering,hoch

TABLE A.1: NASA-TLX Questionnaire (German)

Id	Question title	Question description	Interval
1	Mental demand	How much mental and perceptual activity was required (e.g. thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?	Low/High
2	Physical demand	How much physical activity was required (e.g. pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding slow or brisk, slack or strenuous, restful or laborious?	Low/High
3	Temporal demand	How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?	Low/High
4	Performance	How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?	Good/Poor
5	Effort	How hard did you have to work (mentally and physically) to accomplish your level of performance?	Low/High
6	Frustration level	How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content relaxed and complacent did you feel during the task?	Low/High

TABLE A.2: NASA-TLX Questionnaire (English)

A.1.2 Big Five-Inventory (BFI)-10

The five-factor model of personality (Big Five model) is currently the most widely used model for describing the overall personality. The model contains the five abstract dimensions (also: factors) extraversion, compatibility, conscientiousness, neuroticism and openness (Amelang and Bartussek, 2001). The Big Five-Inventory (BFI) John, Donahue, and Kentle, 1991; John and Naumann, 2010; Rammstedt, 1997; Rammstedt, 1997 was developed to provide a method that records the Big Five independently of the respective scientific schools, i.e. the prototypical five factors of personality. For survey research, however, all these instruments are usually too long. The BFI-10 Rammstedt and John, 2007; John and Naumann, 2010 was therefore developed to enable the five main dimensions of personality to be recorded in research contexts that are subject to strong temporal and monetary restrictions (e.g. surveys).

The BFI-10 consists of 10 items, two for each dimension of personality. Neuroticism is covered by items 4 and 9, extraversion by items 1 and 6, openness by items 5 and 10, tolerance by items 2 and 7 and conscientiousness by items 3 and 8. Each of the dimensions is covered by one positive and one negative poled item. Items 1, 3, 4, 5 and 7 are negatively poled. A five-level rating scale from "strongly disagree" (1) to "strongly agree" (5) is available for the interviewee's answers.

Id	Question title
1	Ich bin eher zurückhaltend, reserviert.
2	Ich schenke anderen leicht Vertrauen, glaube an das Gute im Menschen.
3	Ich bin bequem, neige zur Faulheit.
4	Ich bin entspannt, lasse mich durch Stress nicht aus der Ruhe bringen.
5	Ich habe nur wenig künstlerisches Interesse.
6	Ich gehe aus mir heraus, bin gesellig.
7	Ich neige dazu, andere zu kritisieren.
8	Ich erledige Aufgaben gründlich.
9	Ich werde leicht nervös und unsicher.
10	Ich habe eine aktive Vorstellungskraft, bin fantasievoll.

TABLE A.3: Big Five-Inventory (BFI)-10 (German)

Id	Question title
1	I'm more reserved, reserved.
2	I easily trust others, believe in the good in people.
3	I am comfortable, tend to be lazy.
4	I am relaxed, do not let stress upset me.
5	I have little artistic interest.
6	I come out of myself, I am sociable.
7	I tend to criticize others.
8	I complete tasks thoroughly.
9	I get easily nervous and insecure.
10	I have an active imagination, I am imaginative.

TABLE A.4: Big Five-Inventory (BFI)-10 (English)

A.1.3 Preference for Consistency Scale (PCS)

The questionnaire Preference for Consistency Scale (PCS) is a tool to measure the personality trait for the preference for consistency. This questionnaire is able to identify individuals who would be susceptible and not susceptible to a number of traditional consistency effects - cognitive balance, "foot-in-the-door" and dissonance. The questionnaire was design, examined, and published by Cialdini, Trost, and Newsom, 1995.

That way, Table A.6 shows the original version in English, whilst Table A.5 shows the translated version in German, which is also used in this work. The tables show a identification number and the question title that were presented to the respondents. The scale for each question consists of a (1) Strongly Disagree, (2) Disagree, (3) Somewhat Disagree, (4) Slightly disagree, (5) Neither Agree nor Disagree, (6) Slightly agree, (7) Somewhat agree, and (8) Strongly Agree.

Id	Question title
1	Ich ziehe es vor, mit Menschen zusammen zu sein, deren Reaktionen ich vorhersehen kann.
2	Es ist mir wichtig, dass meine Handlungen mit meinen Überzeugungen übereinstimmen.
3	Auch wenn mir meine Einstellungen und Handlungen untereinander konsistent erschienen, würde es mich stören, wenn sie in den Augen anderer nicht konsistent erschienen.
4	Es ist mir wichtig, dass diejenigen, die mich kennen, vorhersagen können, was ich tun werde.
5	Ich möchte von anderen als eine stabile, vorhersehbare Person beschrieben werden.
6	Bewundernswerte Menschen sind beständig und berechenbar.
7	Das Auftreten von Konsistenz ist ein wichtiger Teil des Bildes, das ich der Welt präsentiere.
8	Es stört mich, wenn jemand, auf den ich angewiesen bin, unberechenbar ist.
9	Ich mag es nicht, so zu tun, als wäre ich unbeständig.
10	Ich fühle mich unwohl, wenn ich feststelle, dass mein Verhalten meinem Glauben widerspricht.
11	Eine wichtige Voraussetzung für jeden Freund von mir ist die persönliche Konsistenz.
12	Ich ziehe es typischerweise vor, die Dinge auf die gleiche Weise zu machen.
13	Ich mag keine Menschen, die ständig ihre Meinung ändern.
14	Ich möchte, dass meine engen Freunde berechenbar sind.
15	Es ist mir wichtig, dass andere mich als einen stabilen Menschen betrachten.
16	Ich bemühe mich, anderen gegenüber einheitlich zu erscheinen.
17	Ich fühle mich unwohl, wenn ich zwei Überzeugungen habe, die uneinheitlich sind.
18	Es stört mich nicht viel, wenn meine Handlungen inkonsistent sind.

TABLE A.5: Preference for Consistency Scale (PCS) (German)

Id	Question title
1	I prefer to be around people whose reactions I can anticipate.
2	It is important to me that my actions are consistent with my beliefs.
3	Even if my attitudes and actions seemed consistent with one another to me, it would bother me if they did not seem consistent in the eyes of others.
4	It is important to me that those who know me can predict what I will do.
5	I want to be described by others as a stable, predictable person.
6	Admirable people are consistent and predictable.
7	The appearance of consistency is an important part of the image I present to the world.
8	It bothers me when someone I depend upon is unpredictable.
9	I don't like to appear as if I am inconsistent.
10	I get uncomfortable when I find my behavior contradicts my beliefs.
11	An important requirement for any friend of mine is personal consistency.
12	I typically prefer to do things the same way.
13	I dislike people who are constantly changing their opinions.
14	I want my close friends to be predictable.
15	It is important to me that others view me as a stable person.
16	I make an effort to appear consistent to others.
17	I'm uncomfortable holding two beliefs that are inconsistent.
18	It doesn't bother me much if my actions are inconsistent.

TABLE A.6: Preference for Consistency Scale (PCS) (English)

A.2 Questionnaire DLT-based Participation in Forestry

Umfrage zur Partizipation in der Waldbewirtschaftung

Ihr Feedback ist entscheidend für unsere Forschung zum Einsatz digitaler Technologien zur Beteiligung im Wald von Bürgerinnen und Bürgern. Wir würden uns sehr freuen, wenn Sie diesen Fragebogen ausfüllen könnten. Vielen Dank für Ihre Mithilfe!

Fragegruppe 1

a) Bitte nennen Sie Ihr Geschlecht: o weiblich o männlich o divers

b) Bitte nennen Sie Ihr Geburtsjahr: __________

c) Bitte nennen Sie Ihren Bildungsgrad: ____________________

d) Bitte nennen Sie Ihren Beruf: ____________________

e) Ihre Kenntnisse zur Waldbewirtschaftung: gar keine o o o o o umfassend

f) Sind Sie global mit der derzeitigen Situation des Waldes zufrieden? überhaupt nicht o o o o o vollkommen

Fragegruppe 2: Stellen Sie sich nun vor, Sie könnten in der Bewirtschaftung von Wald mitentscheiden. Bitte tragen Sie Ihre Präferenz für die verschiedenen Einflussstärken von **1 (am wichtigsten)** bis **5 (am wenigsten wichtig)** in die folgende Tabelle ein.

Ausprägung	Beschreibung	Rang
Informierend	Nur die Bereitstellung von Material zu Informationszwecken, um dabei zu helfen, ein Verständnis über Probleme, Lösungen, etc. aufzubauen.	
Konsultierend	Einholung von Feedback der Beteiligten zu Analysen, Lösungsansätzen, Entscheidungen.	
Involvierend	Bedenken und Wünsche der Beteiligten werden im gesamten Prozess eingeholt und berücksichtigt.	
Kollaborierend	Beteiligte werden am Entscheidungsprozess beteiligt (Gestaltung von Alternativen, Entwicklung von Lösungsansätzen, etc.).	
Ermächtigend	Entscheidungsbefugnis liegt vollständig in der Hand der Beteiligten.	

Fragegruppe 3: Neue Technologien versprechen Vorteile in der Wald-Partizipationspraxis. Bitte bewerten Sie die folgenden Eigenschaften mit Bezug auf die Partizipation im Wald. Im unteren Teil der Tabelle geben Sie jeweils an, ob Sie – ausgehend von der Mitte – eher zur linken oder rechten Ausprägung tendieren.

a) Geteiltes Wissen. Das Wissen rund um den Wald wird geteilt. Jeder verfügt über eine eigene Kopie. Das System stellt sicher, dass das Wissen automatisch aktualisiert wird.

Wie zufrieden sind Sie mit der heutigen Situation des Waldes mit Bezug auf diese Eigenschaft?				Wären Sie bereit, für die Umsetzung eigene Ressourcen (etwa Zeit, Geld, etc.) einzubringen?			
Sehr wenig			Sehr viel	Sehr wenig			Sehr viel
o	o	o	o	o	o	o	o
Das Wissen ist zentral.	Absolut dominierend o	deutlich wichtiger o	etwas wichtiger o	etwas wichtiger o	deutlich wichtiger o	Absolut dominierend o	**Das Wissen ist geteilt.**

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FIGURE A.1: Questionnaire 1/2 for the DLT-based participation in forestry

b) Vertrauenswürdigkeit. Die neueste Version aller Kopien wird gemeinschaftlich ermittelt. Die Macht neue Informationen einzubinden ist verteilt auf jeden Beteiligten (nicht zentral bei Waldbesitzer*innen).

Wie zufrieden sind Sie mit der heutigen Situation des Waldes mit Bezug auf diese Eigenschaft?				Wären Sie bereit, für die Umsetzung eigene Ressourcen (etwa Zeit, Geld, etc.) einzubringen?			
Sehr wenig			Sehr viel	Sehr wenig			Sehr viel
o	o	o	o	o	o	o	o
Vertrauen und Macht zentral.	Absolut dominierend o	deutlich wichtiger o	etwas wichtiger o	etwas wichtiger o	deutlich wichtiger o	Absolut dominierend o	**Macht und Vertrauen verteilt.**

c) Unveränderlichkeit. Das Wissen rund um Wald ist **nicht** veränderbar. Veränderungen sind nachvollziehbare Ergänzungen. Nichts geht verloren.

Wie zufrieden sind Sie mit der heutigen Situation des Waldes mit Bezug auf diese Eigenschaft?				Wären Sie bereit, für die Umsetzung eigene Ressourcen (etwa Zeit, Geld, etc.) einzubringen?			
Sehr wenig			Sehr viel	Sehr wenig			Sehr viel
o	o	o	o	o	o	o	o
Wissen ist veränder-bar.	Absolut dominierend o	deutlich wichtiger o	etwas wichtiger o	etwas wichtiger o	deutlich wichtiger o	Absolut dominierend o	**Wissen ist nicht ver-änderbar**

d) Transparenz. Informationen und deren Bereitsteller sind für alle Beteiligten einsehbar, es gibt keine Zugriffsbeschränkungen. Dies betrifft vergangene genau wie neue Informationen.

Wie zufrieden sind Sie mit der heutigen Situation des Waldes mit Bezug auf diese Eigenschaft?				Wären Sie bereit, für die Umsetzung eigene Ressourcen (etwa Zeit, Geld, etc.) einzubringen?			
Sehr wenig			Sehr viel	Sehr wenig			Sehr viel
o	o	o	o	o	o	o	o
Bestimmte Akteure sehen alles.	Absolut dominierend o	deutlich wichtiger o	etwas wichtiger o	etwas wichtiger o	deutlich wichtiger o	Absolut dominierend o	**Jeder sieht alles.**

Bitte führen Sie mit Bezug auf oben genannte Eigenschaften ein Ranking von **1** (am wichtigsten) bis **4** (am wenigsten wichtig) durch:

Eigenschaft	Geteiltes Wissen	Vertrauenswürdigkeit	Unveränderlichkeit	Transparenz
Rang				

Fragegruppe 4: Abschließende Fragen

Bitte ranken Sie die folgenden Waldfunktionen von 1 (wichtig) bis 3 (unwichtig).

Funktion	Schutzfunktion	Nutzfunktion	Erholungsfunktion
Rang			

Wie ausgeprägt sind Ihre Kenntnisse zum Thema Blockchain?

Nicht vorhanden				Experte
o	o	o	o	o

Vielen Dank für Ihre Mitwirkung. Sie helfen damit der Forschung!

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FIGURE A.2: Questionnaire 2/2 for the DLT-based participation in forestry

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