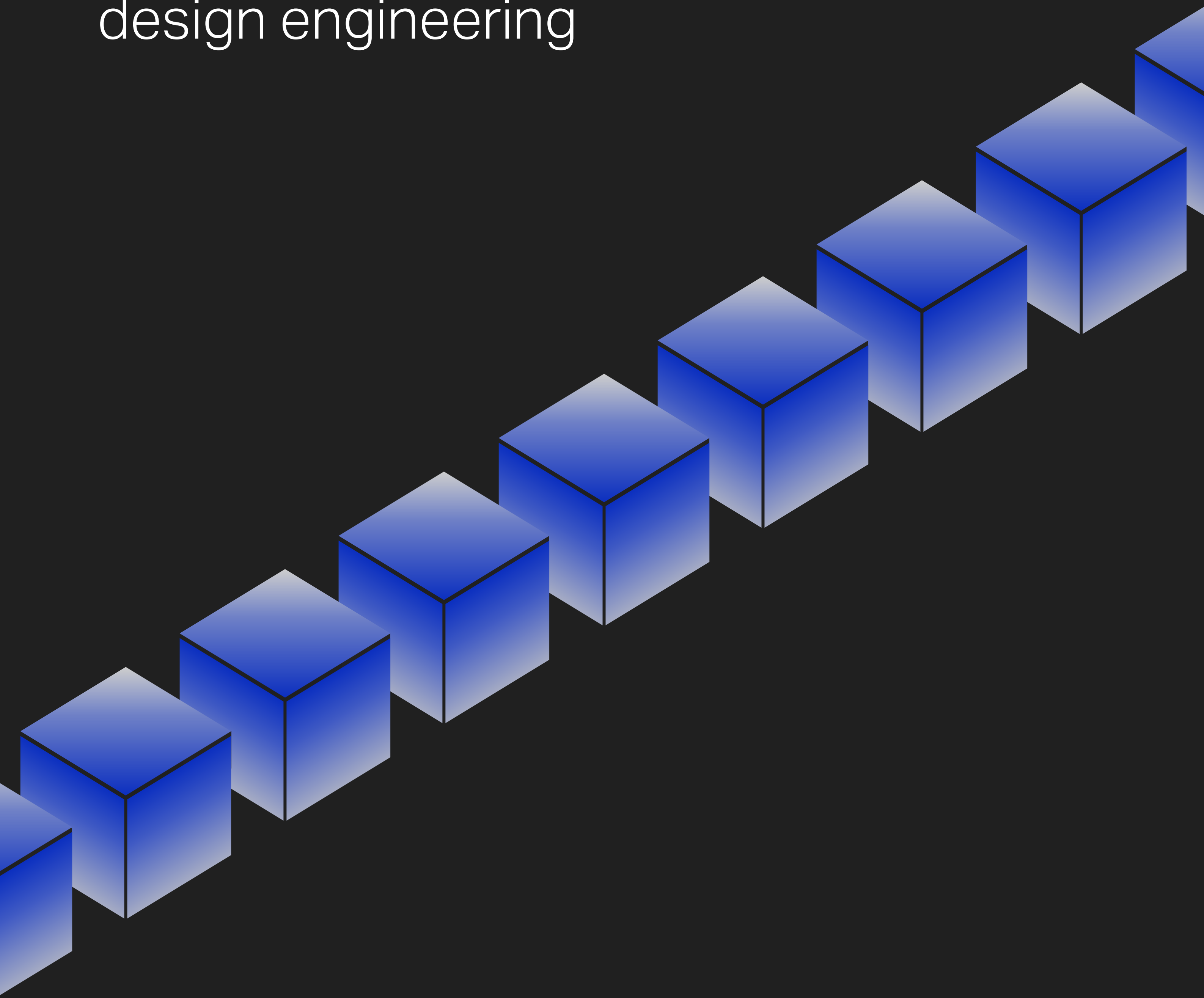
The value of blockchain

Potential and applications within design engineering



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Design & Engineering Master Program

The value of blockchain: Potential and applications within design engineering

Master Thesis

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(equivalent to Master of Science)

In the Design & Engineering degree program

submitted by

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Affidavit

I hereby declare that I have prepared this thesis independently and by my own hand, without unauthorized assistance and exclusively using the sources and aids listed.

Milan, 20. December 2022

Robert Anton Wecken

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Abstract

The relatively new blockchain technology has been subject to much public discussion due to its significant impact on the financial and, more recently, the art industry. As a type of distributed ledger, blockchain technology allows for the instalment of a decentralised database architecture that features several unique attributes regarding data transparency, immutability, and security. This paper investigates blockchain's value and potential for design engineering-related applications in the context of consumer electronics. To provide readers with a shared background, the key fields of study are briefly introduced, including blockchain technology, design engineering and consumer electronics. Next, the research design is presented, which includes two distinct methodologies, a systematic literature review and a multiple case study, which are integrated within a custom research framework. After developing, documenting, and discussing the research results, several specific blockchain application areas with high potential or value were identified throughout the design engineering value stages. A common denominator among the individual applications was blockchain's ability to reconfigure existing IT infrastructures and entire operation schemes, especially within Industry 4.0-related projects. Despite its potential and value, blockchain's mass adoption is faced with significant implementation challenges due to its uncompetitive performance and scalability. Overall, it can be said that blockchains can be considered an enabling technology which needs to be further developed and complemented with other context-specific technologies and non-technical systems to be operational and extract value from its architecture and features.

Keywords: Blockchain, Design Engineering, Consumer electronics, Industry 4.0, Supply chain, Circular economy

Astratto

La tecnologia blockchain, relativamente nuova, è stata oggetto di molte discussioni pubbliche a causa del suo impatto significativo sull'industria finanziaria e, più recentemente, su quella artistica. Come tipo di registro distribuito, la tecnologia blockchain consente l'installazione di un'architettura di database decentralizzata che presenta diversi attributi unici in termini di trasparenza, immutabilità e sicurezza dei dati. Questo articolo analizza il valore e il potenziale della blockchain per le applicazioni legate all'ingegneria del design nel contesto dell'elettronica di consumo. Per fornire ai lettori un background condiviso, vengono introdotti brevemente i principali campi di studio, tra cui la tecnologia blockchain, l'ingegneria del design e l'elettronica di consumo. Successivamente, viene presentato il progetto di ricerca, che comprende due metodologie distinte, una revisione sistematica della letteratura e uno studio di casi multipli, integrati in un quadro di ricerca personalizzato. Dopo aver sviluppato, documentato e discusso i risultati della ricerca, sono state identificate diverse aree applicative specifiche della blockchain con un elevato potenziale o valore nelle fasi di progettazione. Un denominatore comune tra le singole applicazioni è stata la capacità della blockchain di riconfigurare le infrastrutture IT esistenti e gli interi schemi operativi, in particolare nell'ambito di progetti legati all'Industria 4.0. Nonostante il suo potenziale e il suo valore, l'adozione di massa della blockchain si scontra con significative sfide d'implementazione a causa delle sue prestazioni e della sua scalabilità non competitive. Nel complesso, si può affermare che la blockchain può essere considerata una tecnologia abilitante che deve essere integrata con altre tecnologie specifiche del contesto e sistemi non tecnici per essere operativa ed estrarre valore dalla sua architettura e dalle sue caratteristiche.

Parole chiave: Blockchain, Design Engineering, Elettronica di consumo, Industria 4.0, Supply chain, Economia circolare

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1 Introduction

It is well reported that the professions within the design & engineering competencies are constantly and rapidly evolving within almost every aspect, including the used methodologies, technologies, techniques, tools, and skill sets, even venturing into entirely new industries. The upcoming of the relatively new blockchain technology is seen by many as potentially the next big thing regarding the distribution, processing, and storage of data and information. Like during the early days of the internet, it is challenging to foresee use cases and applications at this stage of fundamental information technology; however, some studies suggest that blockchain shows essential characteristics of being a *General-Purpose Technology* (GPT) like electricity, the wheel, and the computer [1]. In light of the above, this thesis investigates blockchain technology's potential and value in design engineering within the context of consumer electronics. To understand this effect, the paper follows a specifically constructed research framework (see section 3) where blockchain implementation proposals and applications are systematically observed within the key value stages of the product lifecycle, including design & development, production & supply chain, and circular economy & waste management. Consumer electronics is an industry, especially relevant, affecting the lives of billions of people every day, not only through the usage of their products but also with regard to how they are designed, procured, made, distributed, and disposed of. As a result, changes to their related processes within their product lifecycle can result in extensive social, economic, political, and ecological consequences. Hence, the consumer electronics industry can be considered a highly significant research environment. In line with the above-mentioned purpose of the thesis, the objective is to create an industry-specific, contextual understanding of blockchain technology consisting of both theoretical insights and empirical knowledge gained through practical use cases. This is achieved by utilising two proven methodologies: systematic literature review and multiple case study. The combination of the two allows a representative presentation of knowledge of the scientific community and industry, respectively. Through this approach, readers are enabled to seize opportunities early and shape the course of blockchain's implementation within design and engineering. The paper is organised as follows: Section 2 provides essential background information. Section 3 gives an overview of the research design and methodology. In section 4, results are presented. Finally, section 5 discusses said results and concludes the thesis.

2 Background

This section presents essential information about the key knowledge areas involved in the later research and analysis, including blockchain technology, design engineering and the consumer electronics industry. First, blockchain's unique characteristics and technical features are highlighted. Subsequently, design engineering activities, processes, & competencies in the context of their lifecycle stages are introduced while underlining current challenges & opportunities. Lastly, a brief overview of the consumer electronics industry is given.

2.1 Blockchain technology

With the publishing of the original Bitcoin paper of Satoshi Nakamoto in 2008, the foundations of all current blockchains were set. Originally envisioned to enable a peer-to-peer electronic cash system (Bitcoin), software engineers have steadily developed and adopted the technology since then. It is now used to serve a broad spectrum of projects, applications, and use cases beyond the financial sector.

2.1.1 Blockchain in the context of information technology

Before going into the technical details of the technology, it is important to illustrate where and how blockchains are positioned within the context of information technology to better understand their purpose, potential, and effects.

Current blockchains are built on top of the fundamentals of the internet, with the hardware physically enabling the exchange of information between entities and the internet protocol (TCP/IP) acting as the fundamental network protocol.

On top of these two layers is the blockchain layer, acting as a substitute for traditional databases. Like databases, blockchains are responsible for the storage, retrieval, and management of data.

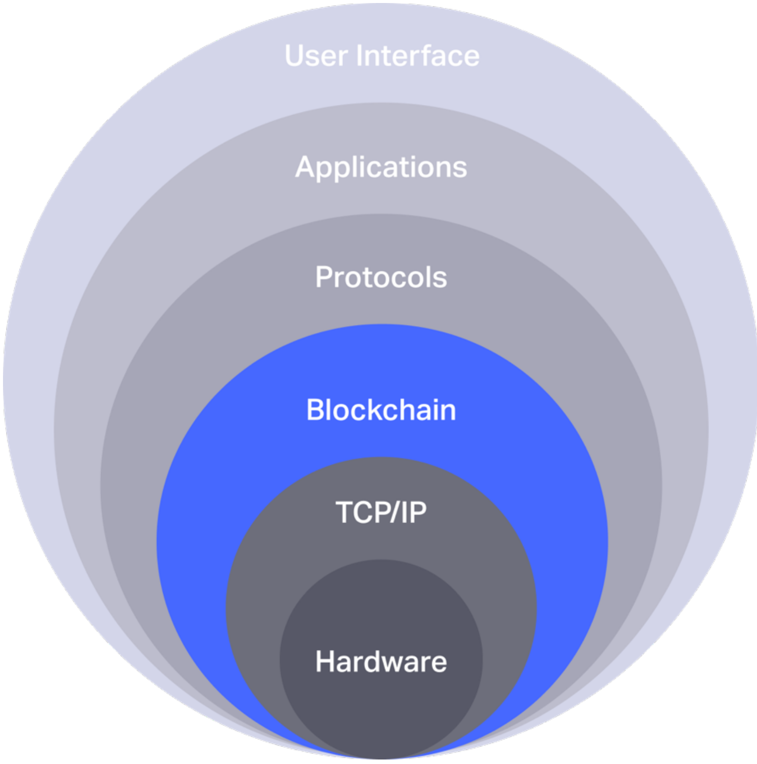


Figure 1: Blockchain within the context of information technology after [16]

Build on the blockchain are the associated protocols, such as the Bitcoin- or Ethereum protocol. These protocols define the rules according to which all transaction activities need to perform.

These technology layers all work together to enable network-based software applications to be executed. The user interface layer provides stakeholders with intuitive surface-level controls. Figure 1 showcases the technology layers within the architecture.

With the above in mind, it can be implied that the value and uses cases of blockchains are not always directly apparent. As a sub-level technology, blockchains have the potential to enable new approaches to building applications, information systems and networks.

2.1.2 Definition and technical working principal

Blockchain is a type of distributed ledger technology. A DLT can be described as a digital database where transactions and data are recorded and shared across multiple nodes/participants of a geographically decentralised network [2].

Blockchains, in particular, are characterized by their structure, where data is stored and transmitted in distinct packages (blocks), which are linearly connected in chronological order, forming a chain. This connection is established by every block containing the cryptographic hash of the previous block.

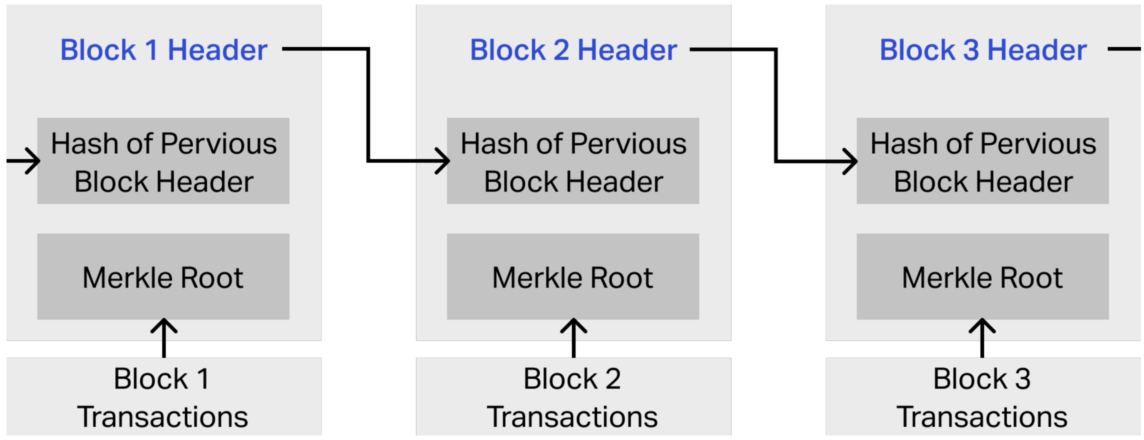


Figure 2: Basic blockchain architecture after [93]

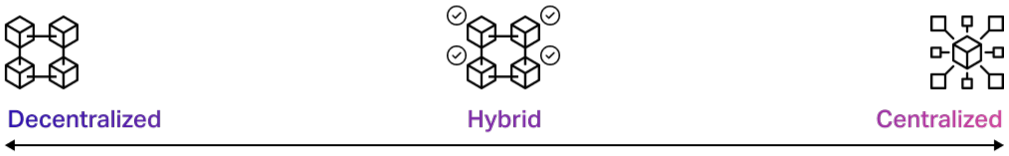
The key motivation for this peer-to-peer approach was to propose an alternative to centrally controlled database systems, such as a bank in the financial industry. Traditional databases require a trusted, central institution which performs transactions between peers. Through the blockchain architecture, peers can directly transact across a decentralised network, verified through a consensus mechanism.

A consensus mechanism can be described as a process through which the network peers find consensus regarding which transactions on the blockchain are valid or not, preventing the double-spending problem of digital assets (see [3]). Different blockchains use different consensus mechanisms, which have distinct qualities regarding their energy use, security, scalability, or performance. Popular consensus mechanisms include Proof-of-Work and Proof-of-Stake, used by the Bitcoin and Ethereum blockchains, respectively [4],[5].

Once a transaction is performed, timestamped, and verified by the network through the consensus mechanism, it is permanently and immutably stored on the blockchain. Alterations of the data are made infeasible, as the cryptographic hash of the associated block would be altered, breaking the link to the previous block of the chain, and leading to a rejection by subsequent blocks. This unique quality of blockchains sets them apart from traditional databases, where theoretically, data can be created, read, updated, and deleted (CRUD) without evidence [6]. For more information about blockchain's technical architecture, readers are referred to [7].

2.1.3 Types of Blockchain

In addition to the well know permissionless or public blockchains such as Bitcoin and Ethereum, which operate on the principle that anyone can read, transact, and participate in the cryptographic-based consensus mechanism, permissioned, consortium-based, or private blockchains have been developed to serve entities which require a different software architecture but still want to take advantage on the core technology. Like permissionless blockchains, permissioned blockchains are still, in essence, decentralized networks of nodes facilitating direct peer-to-peer transactions without a centralized institution. However, nodes or participants in permissioned blockchains need to be initially authorised by a defined centralised or decentralised authority [7], allowing for an alternative consensus mechanism which can enable higher transaction performance, (energy) efficiency, flexibility, and increased privacy but may on the other side compromise regarding its level of decentralisation, immutability, transparency, and security [8].



Type	Permissionless Blockchain	Permissioned Blockchain	Client Server Database
Access	Public	Authorised	Singular
Network Style	Peer to Peer	Private Peer to Peer	Peer to Server to Peer
Data Mutability	Immutable, Append-only	Immutable, Append-only	Mutable, CRUD
Data Privacy	Public Transparency	Network Transparency	Private
Security	High, Public Consensus Mechanism	Medium, Private Consensus Mechanism	Low, Single Point of Attack
Examples	Bitcoin, Ethereum	Hyperledger Fabric	AWS, MS Azure

Figure 3: Blockchain vs traditional databases after [20]

Figure 3 compares both types of blockchain and traditional databases on a decentralized–centralized axis. It becomes evident that there is no one perfect solution for every scenario and application. Each of the three options presented makes different trade-offs regarding the characteristics of databases.

2.1.4 Key blockchain features

In the following, the six key technical features of blockchain technology are presented. These features are of vital importance to the subsequent investigation of blockchain's potential and value as they represent the technology's novelty and differentiation from existing data management solutions. These key features will therefore be incorporated into the source analysis tool, as seen in section 3.

Decentralized architecture

As can be concluded from sections 2.1.2 and 2.1.3, a central characteristic of blockchains is their decentralized ledger architecture. As a system built on top of a peer-to-peer network structure, every node possesses an identical copy of the entire ledger, with no single node owning it [9]. The driving motivations behind decentralised information systems like blockchain are to create a near trust-less environment where participants can interact and transact with each other without trust, reduce levels of control over members of the network, shift away from a centralised authority as well, as increase system security by removing single points of attack [10].

Immutable storage & data security

Reiterating the technical working principle described in section 2.1.2, data recorded on blockchain systems are practically immutable and temper proof through hash functions, cryptography, and a consensus mechanism. Aside from so-called 51% attacks by the majority of a network or other extraordinary circumstances, it is therefore infeasible to modify, update, delete or destroy data [9]. This attribute of blockchains is a crucial differentiator for many prospective adopters, as it supports accountability and fraud prevention. Furthermore, the use of encryption for all data assets ensures the secure transaction of information.

Transaction transparency & traceability

Blockchain's transaction transparency is based on its above-mentioned decentralised architecture, where every transaction is broadcasted to every participant or node of the blockchain network, based on the principle that every node possesses an identical copy of the ledger and new entries must be consented to by the network. Together with the immutable nature of data recorded on the blockchain, transaction transparency enables the tracing of all data entries made on the network, further improving the accountability of the system.

Ownership of data

As an intangible asset, data ownership on the internet and in the digital age has suffered from unauthorised usage, replication, and distribution, potentially even without the knowledge of the owner. Blockchain is a key technology addressing this issue by giving owners control over who has access to the data stored on the blockchain and what transactions are conducted [11]. Through encryption and smart contracts, creators of data can specify who and under which conditions have access to the data stored on the blockchain. Furthermore, any transaction associated with the data is tracked so that the owner is at all times aware of what happens with the data [12].

Incentive mechanisms & token economics

The consensus mechanism of public blockchains is usually based on the promotion of defined non-malicious behaviour by incentivising the creation of protocol-conforming blocks through blockchain-specific crypto assets [7]. This way, the blockchain design can encourage network participants to execute a certain activity. The gained crypto assets can subsequently be used as a form of currency, enabling transactions between participants.

Decentralized apps and smart contracts

Evolving from the relatively simplistic first blockchain implementations focused on digital currency, modern versions of blockchain technology, also called blockchain 2.0, allow for more sophisticated and customisable applications and use cases. Second-generation blockchains like *Ethereum* [13], *Hyperledger Fabric* [14], and the *Internet Computer Blockchain* [15] are characterised by their computational abilities, allowing for the execution of computer code/programs and thereby the building of decentralized software applications (Dapps) without a centralized server [16]. Through this, smart contracts are agreements between two or multiple participants in the blockchain network, formulated as computer code, which is automatically executed once the initially defined conditions expressed in the smart contract are met [17]. The promise of these technical features and the second-generation blockchains, in general, is to disrupt or invent new business models, budling on top of the blockchain decentralized architecture. This foundation transfers some blockchain inherent qualities to the associated Dapps, including no central software ownership, no censorship, built-in payment systems, cryptographic security features, anonymous access, and strong downtime resistance [18].

2.1.5 Blockchain implementation considerations & challenges

In section 2.1.3, it was mentioned that the different types of blockchains might not be suitable for every application or use case. In this section, a number of implementation considerations and challenges are discussed, as they act as important starting points for the following discussion of results later in the thesis.

Data integrity

As a data management system, blockchain technology by itself has no direct control over whether the data recorded on it by the nodes or network entities is trustworthy, accurate, and consistent. Blockchain systems are, therefore, susceptible to the intentional or unintentional submission of false data by good and bad actors. System architectures may utilise smart contract functionality to disincentivise bad actors from intentionally inserting inaccurate data [7].

Data privacy

Due to blockchain decentralised architecture and its corresponding transparency and traceability, the privacy of conducting transactions is inherently compromised, especially regarding permissionless or public blockchains [19]. Permissioned blockchains require the authorisation of an authority for access to the blockchain network, lowering transparency but increasing privacy.

Performance and scalability

Depending on the used consensus mechanism, the transaction performance per time interval greatly varies but is, in general, seen as one of the major drawbacks of blockchain technology. Permissionless blockchains like Bitcoin and Ethereum have TPS (transactions per second) values between 7 and 20, centralised databases operated by the likes of VISA and the Depository Trust & Clearing Corporation can achieve TPS values of up to 100.000 and more [20]. Permissioned blockchains can implement more efficient consensus mechanisms, reaching TPS values of more than 200 [21]. This relatively low transaction performance can hinder the adoption of blockchain technology for large-scale applications, where transactions between hundreds of millions of people must be robustly facilitated on a daily basis.

Energy consumption

Bitcoin, Ethereum and, in general, blockchains are heavily criticised by the public for the high energy consumption required for their operation and the associated negative environmental impact created by the burning of fossil fuels needed to generate said electrical energy. With an annual consumption of 104.89 TWh in 2021, the Bitcoin blockchain required more energy to operate than some countries, including the Philippines and Kazakhstan [22].

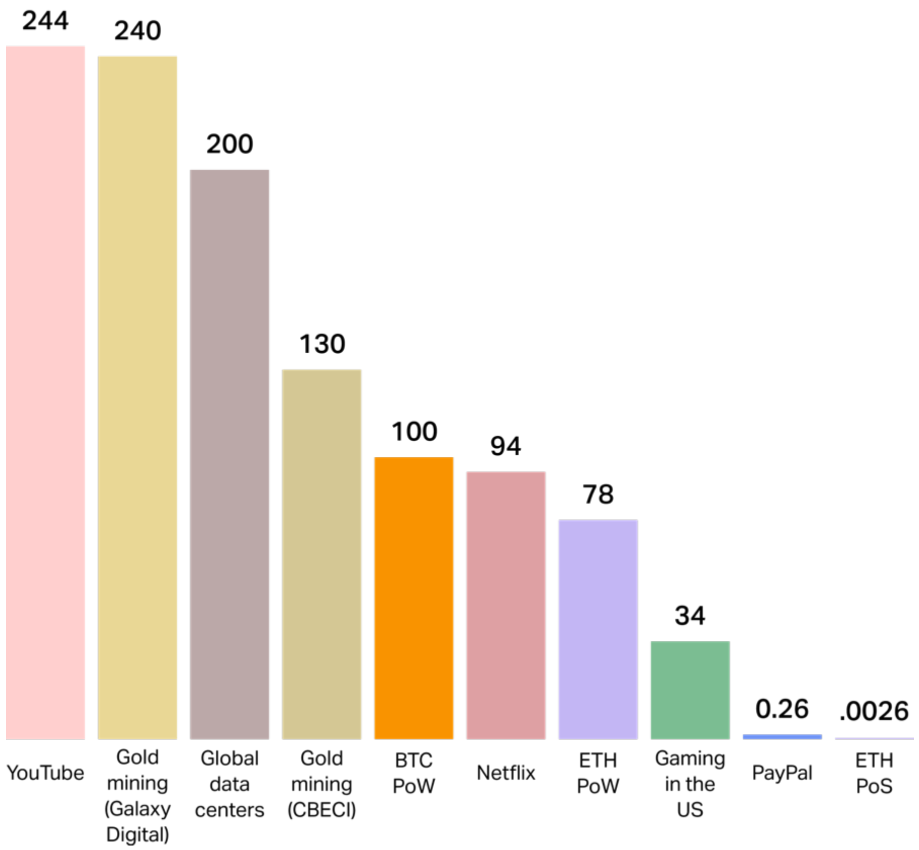


Figure 4: Annual energy consumption in TW/yr after [23]

The energy requirements of a blockchain network are largely depended on the used consensus mechanism, with the Proof-of-Work mechanism being highly energy intensive. Recently, the Ethereum blockchain transitioned from Proof-of-Work to a much more efficient Proof-of-Stake mechanism, reducing its annual consumption by 99.988 % [23].

2.2 Design Engineering

First, it is important to clarify what exactly is meant when talking about design engineering since the term has been extensively used to describe very different activities and processes.

In the context of this thesis, the *European certification of the integrated design engineer* by [24] is used as a reference to define the term design engineering as the integrated and interdisciplinary execution of value-adding processes and activities across the lifecycle of physical products. As stated, the duties and responsibilities of a design engineer go far beyond traditional product development, reaching out deeply into key areas of the product lifecycle. Since the introduction of computer-aided design (CAD), computer-aided manufacturing (CAM), as well as mechanical, thermal, and electrical simulation and digital project management tools, it is evident that advancements in information technology often directly impact the field of design engineering, opening new opportunities how and what types of products can be designed.

In the following section, activities, processes & competencies of design engineering are introduced in more detail within three key lifecycle stages, also emphasising the role of information technology.

2.2.1 Design engineering within product lifecycle stages

A product lifecycle, as defined by ISO 14040:2006, encompasses "*the consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal*".

To understand a product's complete impact regarding resources, energy and labour used, the various stages of its lifecycle need to be assessed. In today's time of global economies, the stages and processes involved reach ever-increasing complexity, especially regarding consumer electronics (see Section 2.3).

For the paper to remain within the scope of the thesis, the analysis will focus on the three key stages relevant to product design engineering:

1. Product design & development

2. Production & supply-chain

3. Circular economy & waste management

Product design & development

The development of products and, in particular, modern consumer electronics requires a truly interdisciplinary approach and numerous competencies from a broad spectrum of fields, including product design, mechanical, electrical and production engineering, computer science, and project management, among others. The work and duties of designers and engineers during product development are therefore no longer isolated and constrained to strictly technical and design-based challenges but reach out to engage between different specialized teams and departments to accommodate the increased complexity of products regarding every discipline and to effectively develop market-competitive products.

This expansion of work and duties is not only horizontal, as described, but also vertical, along the entire value chain. Many processes, from the sourcing of materials and procurement of parts to responsible reusing and recycling, have a direct influence on how products are designed and developed. In addition, completely new approaches to product design & development are constantly explored, with most of them seizing the capabilities of digital technology to optimise product characteristics or production processes. Furthermore, many supportive activities around design and development are challenged regarding their value, efficiency, and security.

Bringing all aspects of the product development process together in a holistic way requires advanced development tools as well as collaboration, communication & coordination methods between said teams and departments. Current software solutions offer great advancements; however, their fundamental centralised architecture can limit them regarding certain security, interoperability, and transparency-related characteristics.

Production & supply chain

This part of the value chain is concerned with the process and procedures which transform the design and development effort into physical, mass-produced products in the hands of consumers. For this transformation to occur, a complex network of independent companies, suppliers, supporting service providers and other economic entities, the supply chain, need to be managed regarding their activities, functions, and facilities to enable production and subsequent distribution.

The management of this supply chain seeks to align and coordinate the participants to match the supply and demand of products as economically, efficiently, and effectively as possible [25]. For this, the adequate quantity and quality of the product, as well as the correct logistical & temporal coordination of the product and its associated materials, components, facilities, and (human) services, must be ensured [26]. In addition, the corresponding flow of information and the financial flow must also be managed. Only when all the above-mentioned factors and the objectives of the participants are aligned, the supply chain can reach its best performance.

In recent times, many supply chains globally have been stressed near complete failure. The complex effects of the global covid-19 pandemic and the Russia-Ukraine conflict highlighted the weaknesses of the systems due to a lack of supplier diversification, insufficient logistics infrastructure and increased energy, raw material, and trading sanctions towards countries like Russia and Belarus [27]. Especially the consumer electronics and automotive industries have suffered greatly from poor-performing supply chains due to a lack of semiconductors, the so-called “chip shortage”. With an exponential increase in demand for micro process and key battery components required for almost all electrical devices and modern cars, the contemporaneous covid-19 conditioned shutdown of many east-Asian suppliers led to a collapse of numerous supply chains, and production stops [28], [29].

In addition to the current stability crisis, supply chains are associated with numerous ethical and ecological issues, including [30] :

- Bribing, corruption, and illegal lobbying
- Low health, safety, and environmental standards
- Forced & child labour, compromised human rights, and working conditions

Design engineers, as well as all members of a business, have a responsibility to resolve these and other issues, as it is essential for creating sustainable supply chains and, therefore, a sustainable global economy. Industry experts [31] suggest that the implementation of a robust digital information management system with sufficient interoperability, adoption rate, high transparency and fraud resilience has great potential to alleviate said issues and challenges. Next to these challenges, there is also the opportunity to overcome issues of trust between entities of the supply chain, fostering collaboration and, thus, economic growth.

Within supply chains, production is one of the key processes, transforming materials, components, and sub-assemblies into the finished product. Numerous new innovations are categorised within the term Industry 4.0, which signifies a paradigm shift towards the data and internet-enabled, digital revolution of industrial sectors like production. The fourth industrial revolution promises intelligent and automated manufacturing of products, procurement of materials and components, management and allocation of resources, and maintenance tracking of industrial assets. Furthermore, new collaborative, customised & distributed production models and a tighter, more direct integration with design and development are conceived. The industry 4.0 project also has the ambition to enable more sustainable production of goods by adopting circular economy approaches facilitated by intelligent management and steering of resources leading to increased efficiency and recuperation of wasted or previously unused resources [32].

Circular economy & waste management

Electronic waste (e-waste) represents the fastest-growing stream of waste in the European Union [33]. It is characterised by its complex composition of different materials [34]. This composition of potentially hazardous materials makes it susceptible to polluting the environment as well as posing a direct and indirect health risk for people working with e-waste or living close to its deposition if not managed correctly. Furthermore, the export of e-waste to less regulated countries leads to an exacerbation of the above-mentioned risks to human health and environmental pollution. Additionally, the extraction of rare minerals and metals from the exported e-waste in conflict areas can lead to the funding of armed conflict and human rights abuses. In total, less than 40% of e-waste is recycled correctly in the EU [33].

To understand the cause of these effects, one can observe the current waste management system. Once a product has been designed, produced, and used by the consumer, it reaches its end of life. As deterministic as this might sound, the journey of a consumer electronics product which has reached the end of its intended use is highly uncertain. The desire of governments, industry, and society for ever greater economic & resource efficiency and a reduced ecological impact coincides towards a circular economy, where several alternatives to conventional (electronic) waste management methods have emerged. As can be seen in Figure 5, the European Union defined a framework laying out the most to least favourable options regarding waste minimisation efforts, from prevention to disposal.

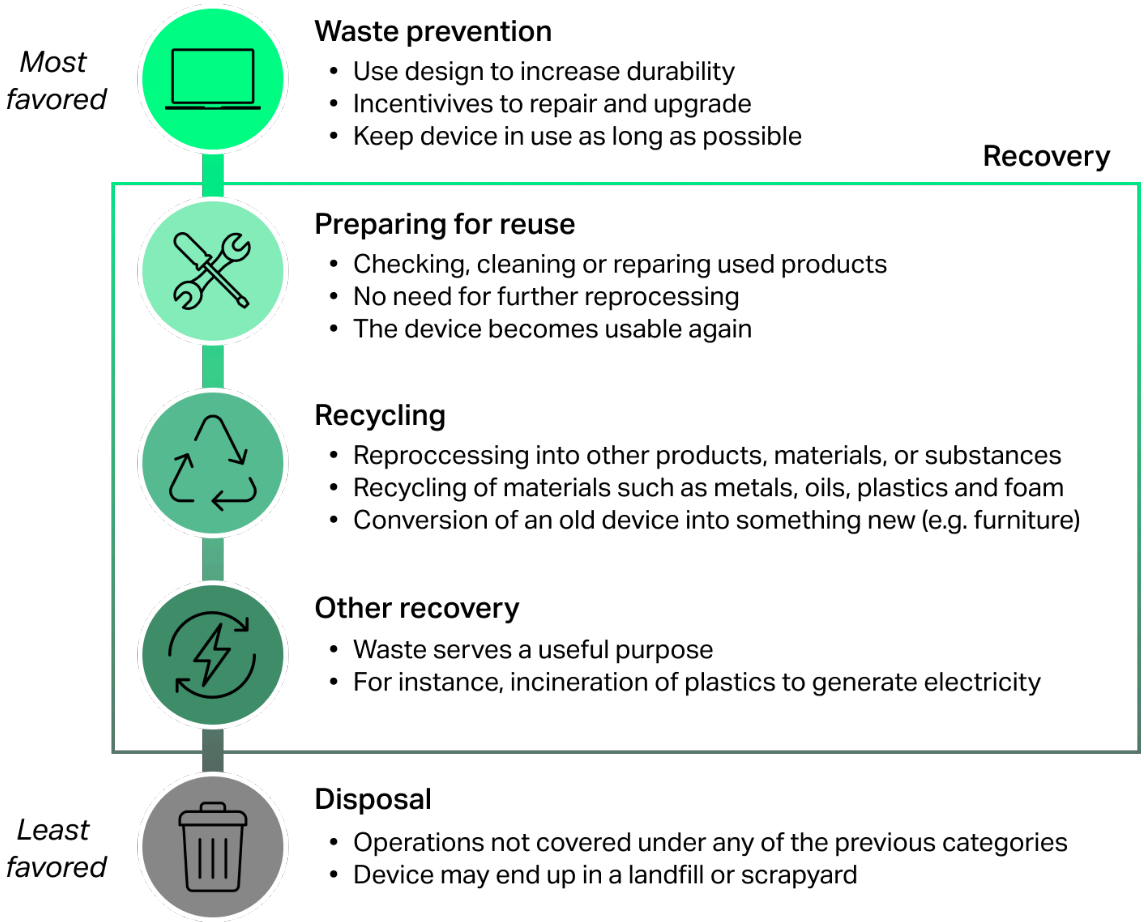


Figure 5: Waste management framework after [34]

The current management of e-waste has significant social, economic & technological challenges and complexities within every stage, including:

- Prevention - Lack of incentives for consumers to use products as long as possible
- Reuse - Insufficient repair friendliness of products
- Recycle & Recovery – Ineffective handling, sortation, and processing of different types of waste & chemicals
- Urban, regional, national, and global logistics, including collection & transport
- Insufficient/varying data collection and reporting methods

Current-day design engineers have a responsibility to create products, processes and systems which are designed towards a circular economy, following the waste management frameworks by the European Union and other countries, prioritising waste prevention, reuse, recycling, and recovery before disposal. Due to its inherently decentralized nature and vast process and handling complexity, no currently available information technology has so far been able to provide a holistic, multinational approach and solution to the waste management system, which integrates all stakeholders.

2.3 Consumer electronics

Consumer electronics (CE) are fixed or mobile electrical devices primarily owned by private households and used for a variety of applications and use cases. Over the last century, CE brought technological advancements to the homes of billions of people, radically transforming their lives in almost every way, including their communication, work, health, education, entertainment, and creative activities. With the introduction of the radio, television, computer, and smartphone, consumer behaviour and the creation, capture, and exchange of data changed holistically.

With the global adoption of consumer electronics (see Figure 6), the relevance and impact of the industry and devices on society, economics and the environment became increasingly significant. These effects can be traced back to processes and actions along the entire lifecycle, from a device's conception to its disposal.

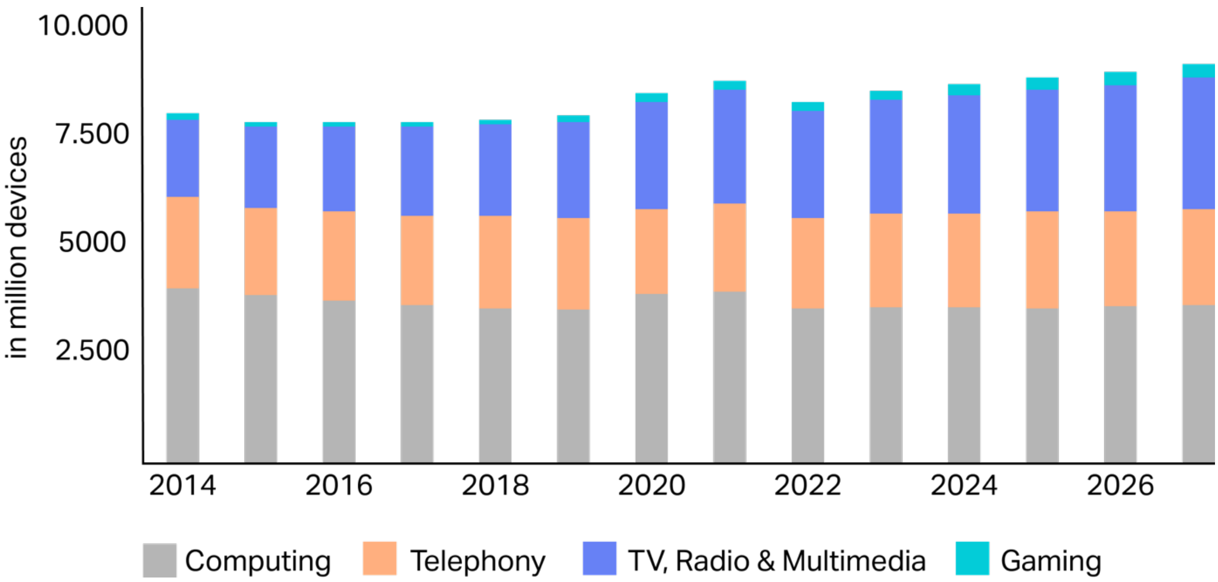


Figure 6: Consumer electronics global sales volume after [35]

With an average of 1.1 devices sold annually to every human on the planet, the vast dimensions of the industry and the involved process become more evident. The associated complexities within the value chain, especially regarding the above-mentioned activities, processes & competencies within product lifecycle stages of design engineers, must be met with the right tools to help transform the CE industry into a more socially, ecologically, and economically sustainable sector of global economics. Innovations within information management systems are predicted to be key factors towards this transformation towards a circular economy.

3 Research design and methodology

In this section of the paper, the used research design and methodology are outlined. To provide the reader with an understanding of blockchain's applications in the context of design engineering and key product lifecycles stages, the paper utilizes a desk research-based framework designed to facilitate two distinct methodologies to provide both theoretical insights and empirical evidence on the matter. Before presenting said framework and methodologies, it is important to define the specific research motivation and purpose with the subsequent formulation of the to-be-answered research questions.

3.1 Research motivation and purpose

As was touched upon in the introduction, the thesis objective is based on the desire to understand the potential and value of the novel blockchain technology in design engineering. In section 2, Background, relevant information regarding the individual topic clusters of the paper, including blockchain, design engineering, and consumer electronics, is discussed. The observant reader will have already perceived the potential present between the challenges faced by design engineering and the technological opportunities of blockchain technology. Since blockchain technology is still a relatively young information technology, the purpose of this paper is to identify its potential in design engineering in consumer electronics as proposed by the scientific community, as well as investigate the value proposition of blockchain within early-stage applications by businesses and organisations.

3.2 Research questions

In order to make the upcoming research and subsequent discussion as precise and beneficial to the reader as possible, three research questions have been defined. The questions are not only advantageous for the reader but also support the author in thinking and conducting the research more clearly, as described by [36]. The two presented sub-research questions, RQ1.1 and RQ1.2 designed to be answered individually by the different methodologies of the research. Afterwards, a holistic answer with all gained knowledge can be given to RQ1, representing the main research question.

RQ1: What is the potential and the value of blockchain features within design engineering in the context of consumer electronics and their life-cycle stages?

RQ1.1: What potential applications of blockchain technology for design engineering are proposed by the scientific community?

RQ1.2: What blockchain-based design engineering solutions and systems exist within consumer electronic life-cycle stages, and what value do they provide?

3.3 Research framework

A specifically designed research framework is introduced to answer the research questions defined in section 3.2 and, in general, fulfil the research purpose (Figure 7). The framework consists of three distinct parts, which represent the stages along which the desk research was conducted.

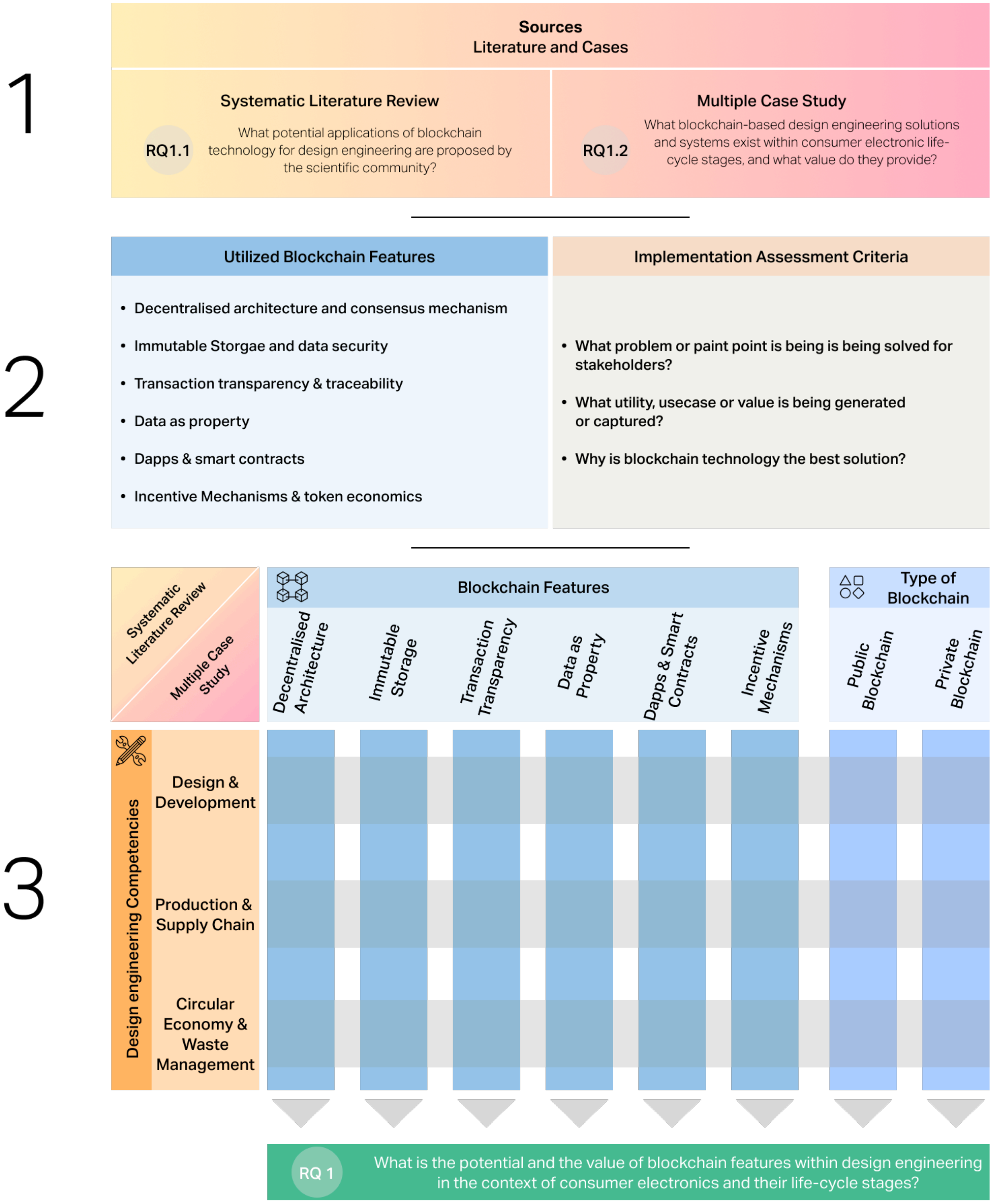


Figure 7: Research framework after [20], [38]

The first part presents the research methodologies used to acquire the sources and information necessary. As mentioned above, the two distinct methodologies are used to provide both theoretical insights and empirical evidence. The systematic literature review is used as a tool to gather a representative selection of academic papers related to the topic. In order to also include empirical evidence of early stage blockchain use cases by businesses and enterprises, a multiple case study is conducted.

In the second part, the source material is analysed and assessed using a custom-designed scheme. Following said scheme, every source is carefully screened regarding the type of blockchain and the exploited blockchain features in its theoretical or practical blockchain-based application, framework, product, or system. Furthermore, three key questions are used to evaluate every source, namely how blockchain provides value or utility, what problems blockchain is designed to solve and why blockchain represents the best solution compared to alternatives. The assessment scheme of part two is designed following the recommendations of [20], [37].

Lastly, in part three of the research framework, the results and findings of both methodologies are separately documented according to the structure seen in part 3 of Figure 7, following the design engineering value stages of consumer electronics and the key blockchain features and types. The structure after [38] provides a visual guideline according to which the systematic literature review and the multiple case study were conducted and documented. This approach directly reflects the interception between the individual value creation stages of design engineering and the identified key blockchain features and types. Through investigating this interception from both a scientific and empirical perspective, its potential and value can be determined. The structured knowledge gathered by the SLR and the MCS is then used to answer the research questions RQ1.1 and RQ1.2, respectively, after which the main research question, RQ1, is answered using all knowledge acquired.

3.4 Systematic literature review

As was described earlier, the purpose of the systematic literature review (SLR) is to obtain theoretical insights regarding the potential of blockchain, answering the proposed research question RQ1.1: *What potential applications of blockchain technology for design engineering are proposed by the scientific community?* To answer this question, the SLR is conducted as described in the subsequent section.

3.4.1 Description & procedure

This section introduces the methodology used. To scientifically evaluate the above-mentioned research questions within the defined scope of this paper, a specifically adjusted systematic literature review (SLR) methodology was implemented based on the snowball approach according to [39] (See Figure 8).

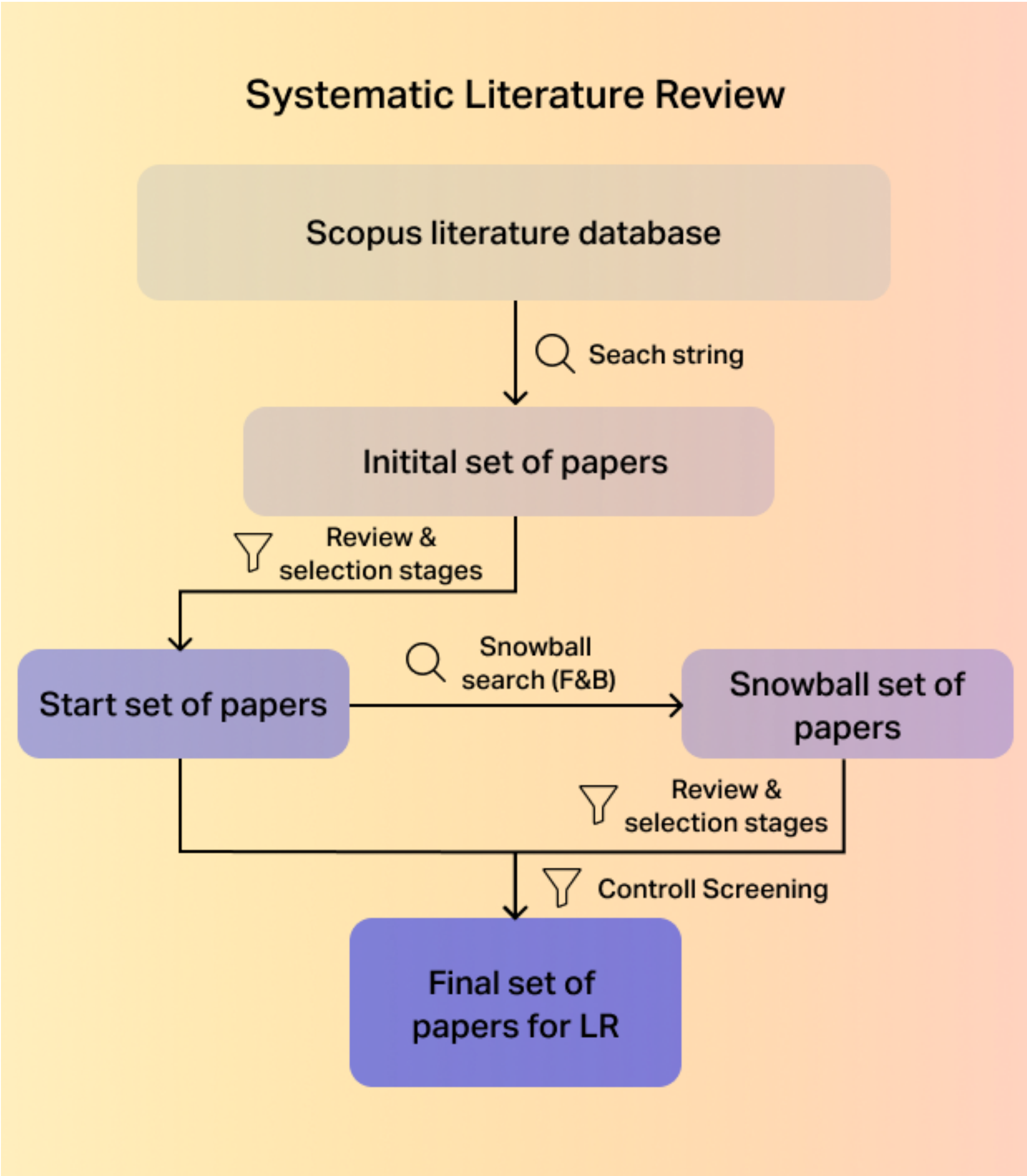


Figure 8: Systematic literature review selection process strategy after [39]

Some carefully selected research boundaries include an initial timeframe from 2019-2022, the source language must be English, the publication stage final, and the source must adhere to the following types: Conference Paper, Article, Review, Book Chapter, Conference Review, thus enabling the research to have a clear and narrow focus.

The snowball-based systematic literature review is based on the assumption that by analysing the references and citations of an initially defined set of papers closely related to the to-be-researched topic, the researcher will obtain a comprehensive selection of papers covering the subject which are representative of the current state of knowledge regarding said subject.

As a first step, the initial set of papers needs to be defined. This set needs to be carefully selected as it functions as the origin of all subsiding papers. Undetected biases, non-peer-reviewed sources, as well as a lack of diversity regarding publishers, authors, and times of publication can drastically influence the quality and scientific integrity of the following analysis. To avoid this, the Scopus database, as the leading abstract and citation database for peer-reviewed scientific literature, was used with a specifically designed search string. The search string is used to find a tentative base set of papers which is subsequently distilled to the final start-set of papers used for the snowball procedure. When defining the search string, the challenge is to obtain a tentative base-set which is at the same time focused, comprehensive, and qualitative with regards to the research topic. During the search-string design phase, close consultation with the thesis supervisor was conducted, taking advantage of her research experience to ensure an optimal balance of said qualities. The resulting search string is presented in Equation 1.

Equation 1: Start-set search string for Scopus (15.09.2022)

```
TITLE-ABS-KEY ( ( blockchain*  OR  distributed-ledger* )  AND  life-
cycle*  OR  plm* )

AND  ALL ( consumer-electronics*  OR  supply-
chain*  OR  production*  OR  product-design*  OR  product-
development*  OR  waste*  OR  recycling* )

AND  ( LIMIT-TO ( PUBSTAGE ,  "final" ) )  AND  ( LIMIT-
TO ( PUBYEAR ,  2022 )  OR  LIMIT-TO ( PUBYEAR ,  2021 )  OR  LIMIT-
TO ( PUBYEAR ,  2020 )  OR  LIMIT-
TO ( PUBYEAR ,  2019 ) )  AND  ( LIMIT-TO ( LANGUAGE ,  "English" ) )
```

Inserted into the advanced search tool of the Scopus database [40], the search string above resulted in 245 papers at the time of writing (15.09.2022). Using the Scopus function “Analyze search results”, the resulting papers of the search can be evaluated regarding several attributes. As can be seen in Figure 9, Figure 10, and Figure 11 the initial sources acquired with the search string from the Scopus database are evenly distributed among different authors, publication years and regions.

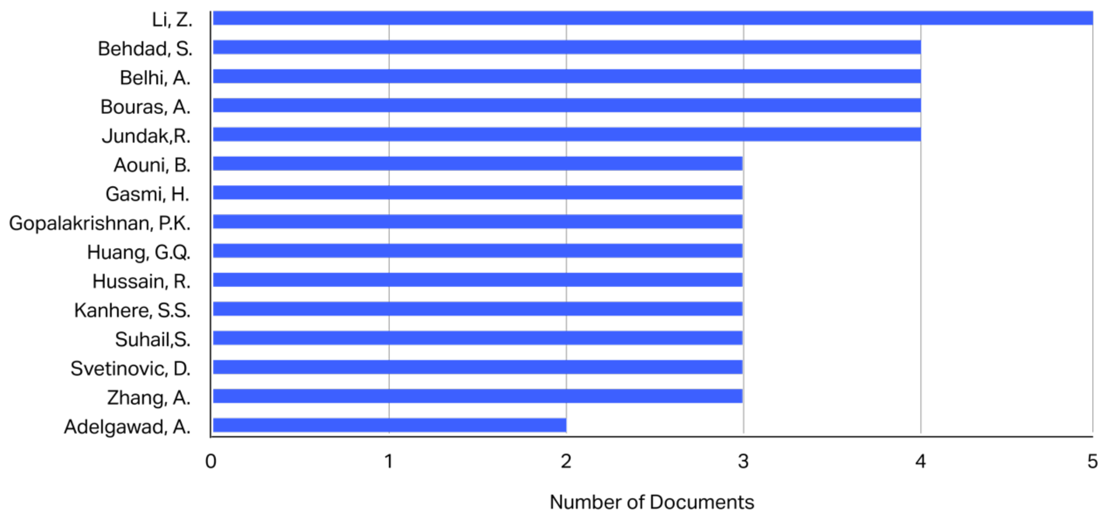


Figure 9: Scopus search analyses: documents by author (top 15)

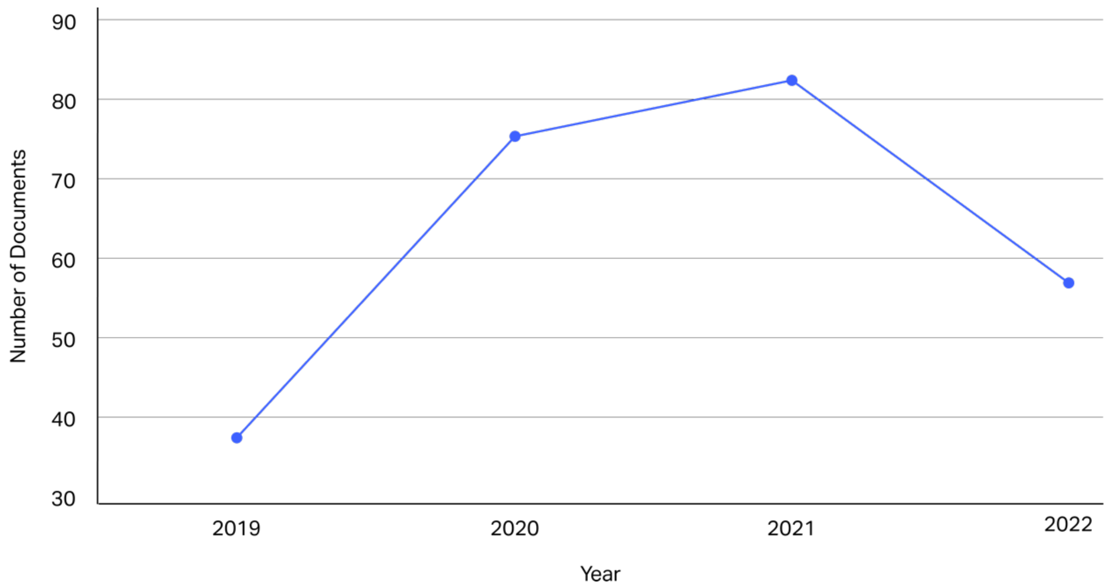


Figure 11: Scopus search analyses: documents by year

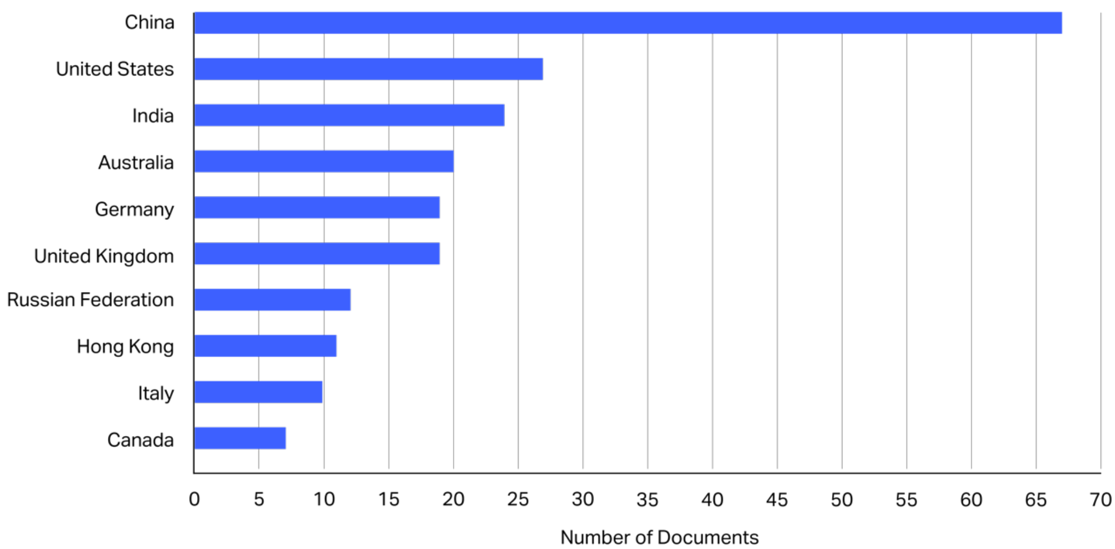


Figure 10: Scopus search analyses: documents by country

Using the Scopus export function, the resulting papers were exported into a *Microsoft Excel* sheet. To distil the tentative base-set into the final start-set of papers, the following selection criteria, as inspired by [41] were checked for each individual paper.

Table 1: Source selection criteria after [41]

Selection criteria	Stage
Relevancy - concerns whether a given study presents relevant findings related to the thesis topic.	1, 2, 3
Only sources written in English are included.	1
Only sources available electronically are included.	1
Only the most recent article is included if multiple studies with the same title by the same authors are found.	2

To archive higher processing efficiency, the selection procedure is conducted in three distinct stages. In the first one, only the source title and key metadata are evaluated. Only if this set of information suggests that the sighted source could be relevant for the thesis the source gets to the next selection stage. The second selection stage reviews all remaining papers in closer detail, including the abstract, version history if present, topic novelty and the number of citations. In the third selection stage, all remaining papers are read in detail, making sure that they are indeed relevant and valuable for the thesis research.

After each stage, the individual sources receive a number from 0 to 3 in the Excel sheet [see Appendix A]. 0 indicates that the paper is irrelevant or is not included for some other reason, as explained by the staging procedure. 1 stands for tentative; further investigation is necessary. 2 means that the paper has potential, and a complete analysis will be conducted. A source with a number 3 is included in the start-set. In every selection stage, sources can only gain one number, resulting in a process where all included sources are reviewed and read in detail.

After the completion of all three stages, the remaining papers represent the start-set. The next step of the snowball-based systematic literature review process is the identification of subsequent, topic-relevant papers referenced by the defined start-set of papers (backwards snowballing) and papers which themselves cite the defined start-set of papers (forward snowballing). While the referenced papers can be identified by the references section of the individual papers of the start-set, the forward snowballing procedure is conducted using the Scopus database, where papers citing the papers in the start-set are listed.

Once the snowballing procedure is executed for every paper of the start-set, the same review and selection procedure as before is conducted to ensure an equal level of relevance and quality. The remaining papers, together with the start-set papers, make up the final set of papers for the subsequent analysis and evaluation. All selection steps for this systematic literature review are recorded in the beforementioned excel sheet [see Appendix A].

3.5 Multiple case study

Alongside conducting a systematic literature review, it is beneficial to supplement the theoretical knowledge with empirical gained insights from analysing a selection of industry cases, supporting or challenging the theoretical findings, which may reveal some intricate details of and relationships between the entities and process involved within blockchain-based systems and design engineering, leading to an increased understanding of the matter. As [42] defines it, the multiple case study methodology can be useful for researchers when "a how or why question is being asked about a contemporary set of events over which the investigator has little or no control". It can therefore be argued that the chosen methodology is appropriate to obtain a deep comprehension of the investigated research area. The results acquired are then used to answer the proposed research question **RQ1.2:** *What blockchain-based design engineering solutions and systems exist within consumer electronic life-cycle stages, and what value do they provide?* As will be described in detail in the next section, the case study is characterised by its exploratory approach. Since blockchain technology is still, relatively speaking, a very young technology, business models and use case a just starting to emerge and mature.

3.5.1 Description & procedure

Like with the systematic literature review, it is important to have a scientific methodology to search for and select appropriate business cases for subsequent analysis and evaluation. As recommended by [42], it is appropriate for the number of final case studies within a multiple case study to enable the in-depth study of each individual cases while representing a spectrum of case to adhere to the exploratory ambition of the thesis. In this paper, each value stage of design engineering is to be represented by two case studies for a total of six case studies. In Figure 12, the corresponding selection procedure is visualised. First, an appropriate database of businesses is selected, as suggested by [43]. *Golden* [44] offers a publicly accessible database of over 1.7 million businesses globally, together with advanced search tools, greatly increasing the likelihood of finding suitable businesses for the case study. First, specifically designed search queries need to be applied to extract an initial set of companies. To obtain the best results possible, the findings from the systematic literature review are utilised to design the search queries used in the *Golden* database. The SLR findings represent strong theoretical evidence for upcoming blockchain-empowered businesses, products, and systems and are, therefore, highly useful for searching for business case studies.

To be as precise as possible, three distinct search queries are created to reflect the three key design engineering value stages, as can be seen in Figure 15, Figure 14, and Figure 13. The exact search queries, as well as the recorded selection process steps, can be found in the corresponding excel sheet in Appendix B.

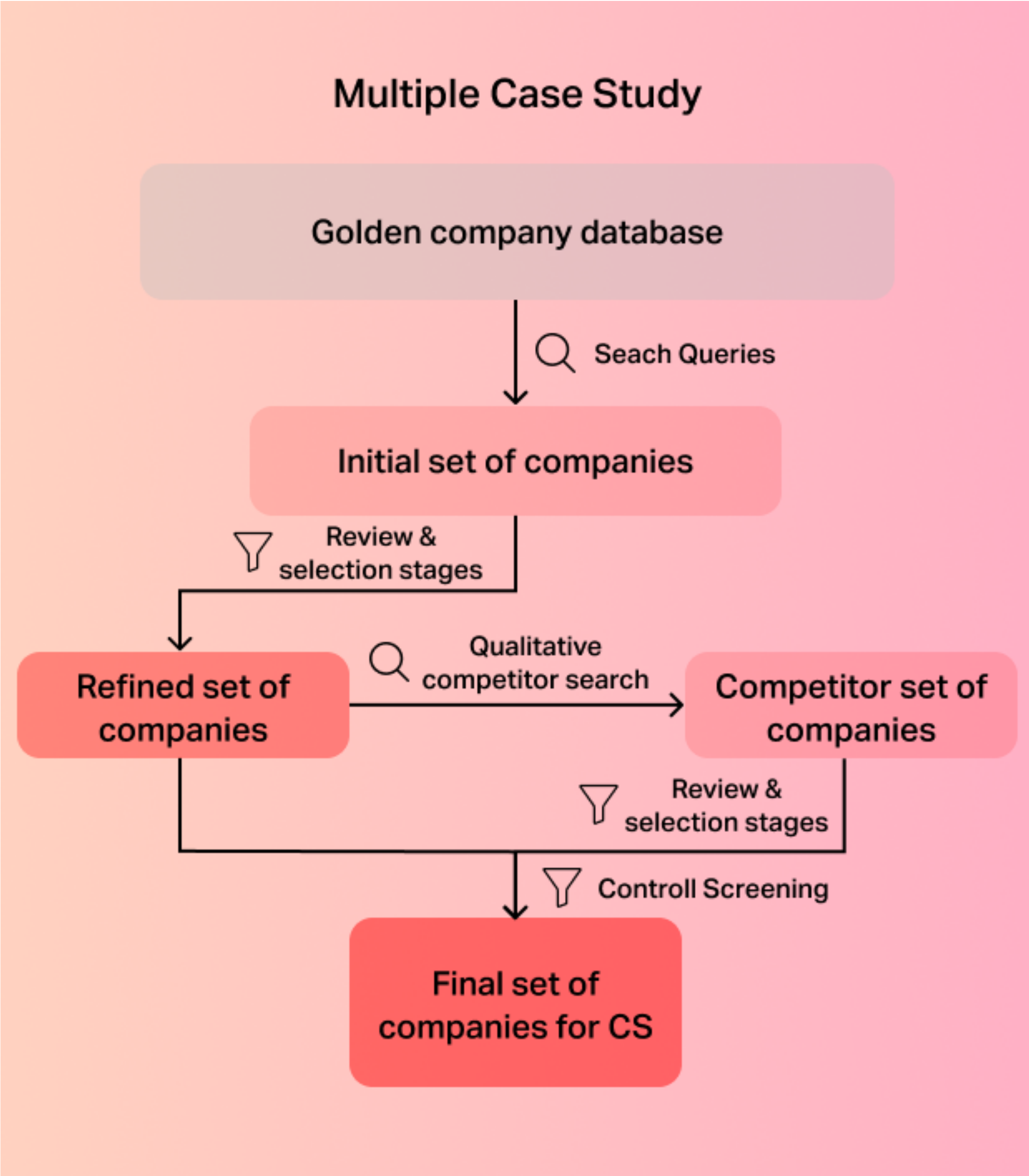


Figure 12: Multiple case study selection process strategy

With the search queries applied, the resulting initial set of companies needs to be reviewed and screened to extract a refined set of companies which meet the requirements for the case study. Based on this set, a qualitative search for similar or competing companies is conducted, as sometimes interesting similar companies are not captured through the search tool. For this, multiple unstructured search techniques were utilised, including numerous databases or search engines like *Crunchbase.com* or *Google.com*, as well as investigating social media connections on *Linkedin.com* and *Twitter.com*. Furthermore, several trade journals and news outlets were searched for competitors or similar companies to the ones identified in the refined set of companies. Finally, a control screening was conducted to ensure that all included companies were legitimate and still in active operation.

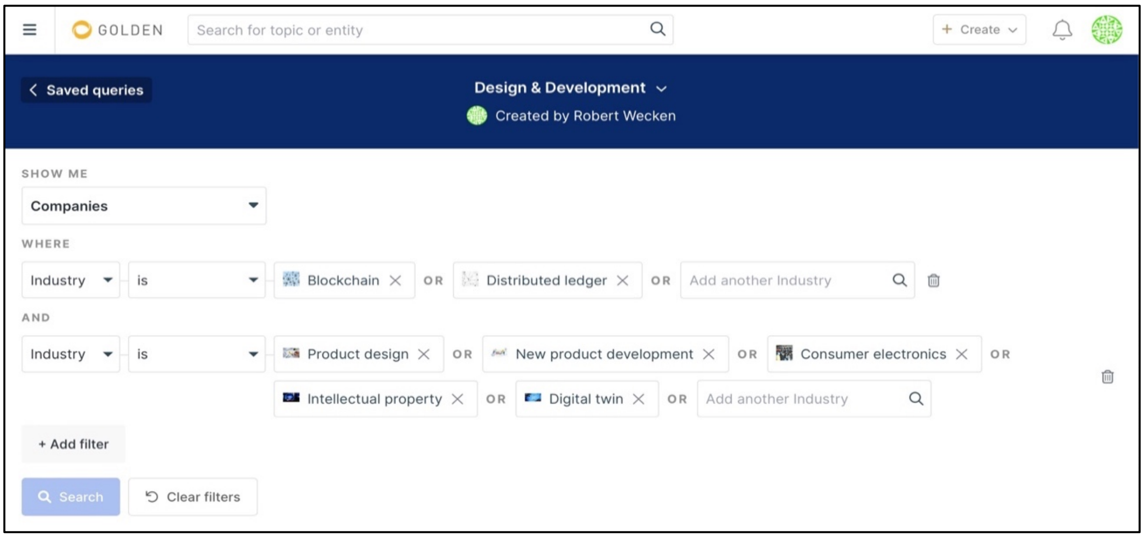


Figure 13: Golden database search string for "Design & Development"

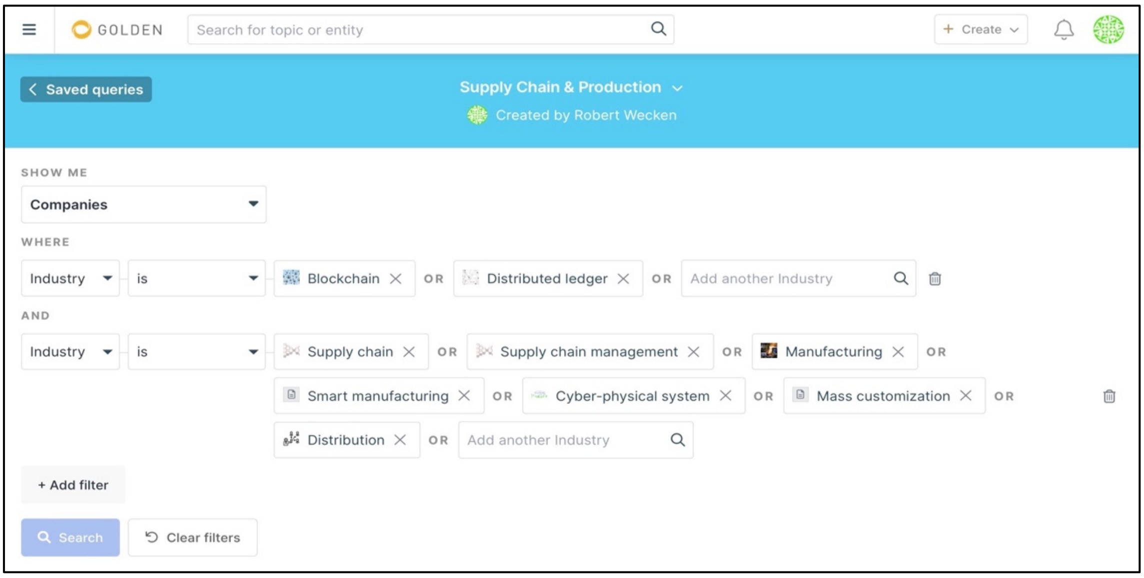


Figure 14: Golden database search string for "Production & Supply-Chain"

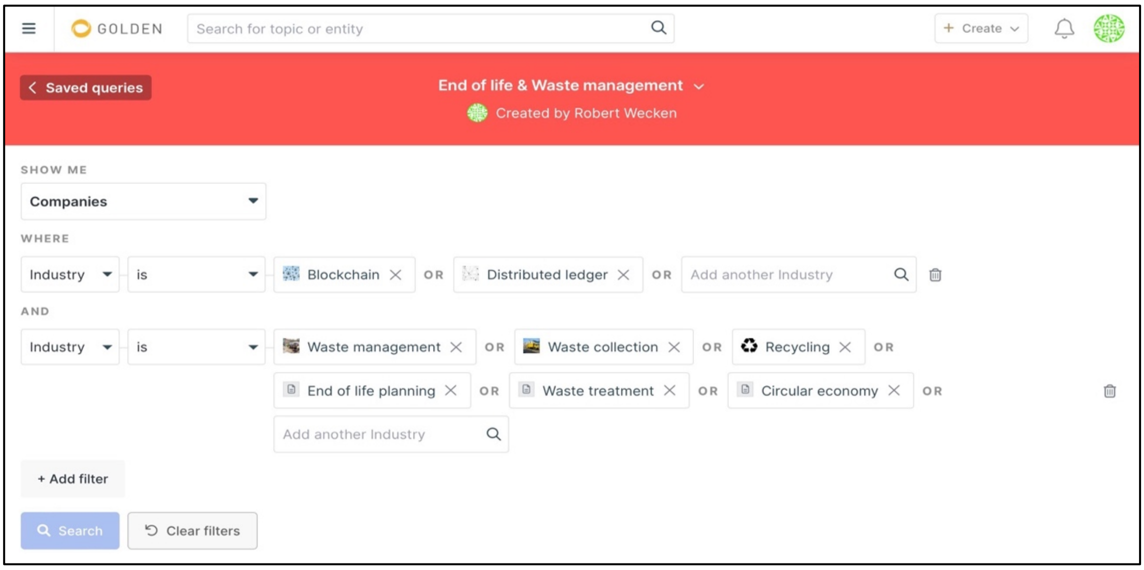


Figure 15: Golden database search string for "End of life & Waste management"

4 Results

4.1 Results of systematic literature review

The execution of the systematic literature review, as described in section 3.4, resulted in a total of 25 individual sources. In the following, the potentials of blockchain technology within design engineering, as identified within these sources by the scientific community, are presented. The results are sorted along the design engineering value stages and further grouped under mutual application categories. Finally, a table following the third stage of the research framework (see Figure 7) summarizes the results within every value stage.

4.1.1 Design & development

As was stated in section 2.2.1, contemporary product design and development is defined by advanced computer-aided tools and the collaboration of large interdisciplinary, inter- and intraorganizational teams, especially in the later detailed development phases of complex, mass-produced products such as consumer electronics. With hundreds or even thousands of individual stakeholders involved in the design and development stage of large corporations, numerous information and data management-related challenges arise, as well as new demands for innovative design and collaboration approaches, together with the drive for ever greater process efficiency and flexibility. As suggested by [45], the centralised architecture of current information & data management systems is no longer preferable and capable of serving the demands of innovative product design and development. In the following, the contributions of the selected literature are presented on how blockchain technology and its features can be utilised to reconstruct and create new information & data management systems, which enable new design and development approaches.

Product design against counterfeiting

The authors of [46] propose a theoretical framework for a smartphone anticounterfeiting system using a decentralised identity management framework based on a permissioned blockchain. Using the proposed system, smartphones and potentially other electronic devices can be designed so that involved parties can execute robust device identity validation and verification services based on blockchain's transparent and immutable architecture, combating significant industry revenue loss due to counterfeiting. Furthermore, the system offers lifecycle tracing, as well as an associated reporting mechanism for stolen devices, which can reduce reporting times from days of a comparable centralised architecture to seconds, using smart contracts. The decentralised architecture of the system promotes faster and wider adoption as no single entity has access to sensible industry data.

The work of [47] goes in a similar direction but focuses on how of the most critical components of any electrical device, the integrated circuit (IC), can be designed to offer enhanced traceability and cloning prevention. ICs have long been plagued with counterfeiting, tampering, and re-packaging issues leading to compromised products regarding their functionality and safety in the hands of consumers. To combat this, the authors propose a blockchain-based IC traceability protocol which uses physically unclonable functions (PUFs) on the IC, which enable a secure link between the individual physical ICs to the blockchain. Smart contracts are used to automatically conduct the associated protocol steps like IC enrolment, authentication, and ownership transfer. With the protocol being hosted on the public Ethereum blockchain, consumers and supply-chain participants can trace and verify the provenance of the IC of the specific device. Again, the architectural characteristics of decentralised blockchain systems enabling said features, including transaction transparency and immutable storage of data, are fundamentally important and cannot be subsidised by a centralised solution.

As was proven in many industries, blockchain has proven to be highly compatible with other modern technologies, often with the resulting functionality exceeding the sum of the individual technologies. This phenomenon is also present in the work of [48], in which the authors make the proposal of designing products which natively combat counterfeits within the supply chain by the implementation of Near-field communication (NFC) chips and blockchain. During manufacturing, the product's essential information, like serial number, name, and expiration date, among others, are permanently recorded on an integrated NFC chip. This allows stakeholders along the product lifecycle to defend against common counterfeiting attacks, including the modification of identity & safety information (e.g., expiration date), the cloning of a product's details for use on a fake product, as well as the transfer of a legitimate information tag from a genuine to a fake product. The defence mechanisms for these attacks are based on several blockchain attributes, including transaction transparency and immutable storage of data, which have been precisely implemented in the author's information management architecture.

Digital twin

In recent times, the idea of a digital twin (DT) of product or system has widely been investigated by academia and industry as potentially the next breakthrough technology within product or system design and development, expanding into all lifecycle stages. As described by [49], *"a Digital Twin is an integrated multiphysics, multiscale, probabilistic simulation of an as-built [product] or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding [physical] twin."* As [50] pointed out, DTs are facilitated by three parts, the physical product, the virtual product and the data transmission between the physical product and the virtual product. Digital twins allow for constant, real-time monitoring of performance and reliability data, as well as enable, together with big data analytics and artificial intelligence (AI), the optimisation of systems or future products. However, the implementation of digital twin systems requires state-of-the-art industrial sensor monitoring systems, as well as an advanced information and data management architecture.

[50] developed a data management method for digital twins of products based on blockchain technology, designed to solve data storage, data access, data sharing, data authenticity, and data overwriting issues. The method is designed as a peer-to-peer network where participants from different lifecycle stages have access to the system. All transactions between participants, as well as the sensor data between the physical and virtual products, are recorded on a decentralised, blockchain-based architecture. This blockchain architecture ensures that the data is shared in a secure manner so as not to compromise the privacy of sensitive data shared by participants.

[51] work has a similar research objective, providing a secure digital twin information management system prototype, EtherTwin, which is based on the Ethereum blockchain protocol, addressing the need for secure data-sharing models for lifecycle parties and a complex ecosystem of interacting Digital Twins. The proposed system contributes to the question of how to implement sophisticated access control functionality so that digital twins can be shared with relevant untrusted lifecycle parties while ensuring confidentiality, integrity, and availability for sensitive information, fostering inter- and intraorganizational collaboration and economic efficiency. The proposed solution utilises smart contracts and takes advantage of blockchain's inherent decentralised architecture, immutable storage, and data security features.

IP protection

With the digitalisation of documents, media, industrial design and engineering data and trade secrets, among others, the protection of intellectual property (IP) has been faced with many challenges. Due to their inherent nature, digital assets are easily used, copied, and distributed by unauthorised actors, violating the owner's usage rights and causing great economic harm and possibility endangering consumers.

[52] has identified major challenges and system inefficiencies of the current global IP protection system, including slow, manual, costly and non-transparent registration processes, missing interconnection of IP registration offices and global IP marketplace, transparency & traceability related supply chain challenges, illiquidity of IP assets. Based on these challenges, the authors investigated multiple cases regarding blockchain technology's impact on the current lifecycle of IP. They identified that smart contracts have the potential to streamline certain IP processes related to registration, as well as to automate certain monetary transactions. Furthermore, Non-fungible tokens (NFTs) were seen as a passage to digital ownership, acting as a unique blockchain-based identification utility [53], providing the owner with enhanced trading, monetisation, protection, and registration capabilities for their digital assets.

Product development process

As was addressed in section 2.21, the development of products is becoming increasingly complex, having to manage and accommodate an ever-increasing amount of information, technologies and processes related to the diverse stakeholders involved.

[45] proposes a blockchain-based framework for efficient and secure management of the information and procedures associated with complex product development by expanding the feature set of conventional product data management systems. The authors utilise blockchains decentralised architecture as well as the technology's immutable storage and transaction transparency and traceability attributes to enable several advantages over a traditional management system, including an affordable data exchange mechanism between OEMs and suppliers, allowing especially small and medium-sized enterprises (SMEs) to work with large corporations in a low-cost, efficient manner. Furthermore, the increased transaction transparency and traceability result in higher accountability for all participating network partners while ensuring data security and privacy through the default data encryption protocols and consensus mechanism of blockchain. These advantages, enabled by the proposed blockchain-based system management framework, have the potential to increase the efficiency &

effectiveness of collaboration between enterprises substantially. Especially for small and medium-sized enterprises, the framework may lower the threshold for collaboration with larger corporations to a level where it is economical for them to participate, representing a breakthrough for their business.

Table 2: Potential of blockchain features on design & development

Blockchain Feature & Type	Applications or use cases	Sources
Decentralised architecture and consensus mechanism	Smartphone anticounterfeiting system, Integrated circuit (IC) cloning prevention, Digital twin data management, Digital product development process	[46],[47],[50],[51],[45]
Immutable storage & data security	Integrated circuit (IC) cloning prevention, Product verification system, Digital twin data management, IP protection, Digital product development process	[47],[48],[50],[51],[52],[45]
Transaction transparency & traceability	Smartphone anticounterfeiting system, Integrated circuit (IC) cloning prevention, Product verification system, IP protection, Digital product development process	[46],[47],[48],[52], [45]
Data as a property	IP protection	[52]
Dapps & smart contracts	Smartphone anticounterfeiting system, Integrated circuit (IC) cloning prevention, Digital twin data management	[46],[47],[51],[52]
Incentive mechanisms & token economics	IP protection	[52]
Permissionless blockchain	Integrated circuit (IC) cloning prevention, Digital twin data management, IP protection	[47],[51],[52]
Permissioned blockchain	Smartphone anticounterfeiting system	[46]

4.1.2 Production & supply-chain

The modern production and supply chain systems can be considered drivers of globalisation and its associated economic prosperity. With contemporary consumer electronics becoming increasingly complex, a highly specialised and decentralised value chain of raw material producers, manufacturers, component suppliers and other supply chain entities has emerged. Section 2.2.1 discusses the issues and challenges associated with this often non-transparent network of entities. In this section, the potential applications of blockchain to solve said challenges and issues of several authors are reviewed and presented.

Supply chain information & collaboration management

The global supply chains associated with consumer electronics are getting increasingly complex, with, in some cases, hundreds of individual supplier companies and stakeholders involved for to produce a singular product.

The authors of [54] have identified traceability and integrity of information to be one of the major challenges within supply chain systems. Their blockchain-based trust management framework, TrustChain, aims to alleviate said challenges, creating trust between supply-chain participants through tracking their interactions and transactions and assigning subsequent trust and reputation scores to the respective participants. Even with utilising blockchain as a secure and tamper-proof storage of information, the tracking of interactions represents the major challenge with this system, as it must be ensured that the data gathered for the trust and reputation scores is credible and trustworthy. The proposed framework overcomes this challenge through the implementation of automated data collection through the industrial internet of things (IIoT) sensor data, supplemented with the recording of certified trade events and transactions, as well as regulatory endorsements. This trusted data is then automatically converted into the trust and reputation scores for each participant using smart contracts. With this approach, key drawbacks of conventional blockchain systems can be circumvented, enabling supply chain entities to transact with each other with a higher level of trust regarding the quality of exchanged goods and services. If implemented, design engineers can make better decisions with whom they want to transact across the entire spectrum of the supply chain based on the corresponding trust score.

With the fast adoption of Industry 4.0 compatible digital tools, sensors, machines, production systems, and factories, the current centralised product lifecycle management (PLM) software solutions can no longer facilitate Industry 4.0 related processes due to the decentralised, interoperable, and open nature of said processes and systems.

In light of these circumstances, [55] developed a blockchain-based PLM framework, which addresses said challenges while ensuring data and information privacy and security. The proposed PLM system provides an open, collaborative peer-to-peer environment for entities involved during the product lifecycle stages to share information among each other and re-integrate dispersed product information from multiple organisations, allowing participating companies to utilise said information better while gaining new inter-organisational insights. Furthermore, the framework allows for automated transaction and alert services through the integration of smart contracts, supporting enterprises to conduct instant decision-making and thereby increasing operational efficiency. Finally, the proposed framework can function as a platform enabling innovative services, including company-consumer co-creation, product tracking and tracing, proactive product maintenance, and regulated recycling services. In summary, the blockchain-based framework functions as a key enabling technology for smart PLM and Industry 4.0, acting as an open but secured cross-enterprise communication and collaboration platform. The work of and collaboration between design engineers is expected to become more efficient, capable, and secure.

[56] developed and blockchain-based interoperability and data-management system to improve collaboration and allow for the seamless sharing of information and data between inter- and intraorganizational entities, specifically between original equipment manufacturers (OEMs) and partnering companies. Current IT solutions were found to be disjointed, non-interoperable, and suffered from a lack of trust by the participating companies. The proposed system offers solutions to multiple identified issues, including a reduced temporal delay while sharing data, improved data consistency across the organisation through the implementation of notifications, and an automated data verification procedure, as well as providing the OEM with enhanced traceability of critical product data across organisations. The theoretical framework was subsequently validated by a proof-of-concept prototype constructed on a permissioned blockchain based on the Hyperledger Fabric architecture.

The authors of [57] have developed a blockchain-based transaction management system designed to be used in the integrated circuit (IC) industry. Motivated by the current centralised transaction model, which suffers from malicious cyberattacks and can therefore be identified as a critical risk for the theft of core technology and intellectual property, the paper proposes a system which solves said problems. It is designed to facilitate the transaction of highly sensitive IC data, including IC layout design documents, technology patents and production process information. To address the performance and privacy issues of public blockchains, the proposed BICTM system utilises the Hyperledger Fabric permissioned blockchain. Custom-designed smart contracts are used to facilitate said transactions. Additional features include digital encryption algorithms and a penalty mechanism to support the defence against attacks and bad actors within the network, as well as real-time monitoring and warning functionality for machine status, blockchain and transaction information.

[58] discusses the security stability of the electronics supply chain on a global scale, dissecting from six stakeholder perspectives, including OEM or IP owner, distributor, assembler, integrator, consumer, and recycler. To address the challenges faced by each stakeholder group, the authors propose a permissioned blockchain-based certificate authority framework, which hosts and manages sensitive chip design information as well as other intellectual property and trade secrets. This system allows all permissioned entities to trace, validate, and accept or deny any transaction on the platform, certifying the authenticity of associated electronic devices. Furthermore, the framework prevents unauthorised recycling, remarking, as well as overproduction and cloning of products which would violate agreed terms with the OEM or IP owner.

Smart & cloud manufacturing systems

The authors of [59] investigate how blockchain technology can enable smart manufacturing systems, archiving a sustainable production of products in the context of Industry 4.0. The paper identifies blockchain applicability for multiple upcoming manufacturing management sub-systems, including smart resource planning and sharing, digital twin manufacturing, operation scheduling, manufacturing execution systems, manufacturing equipment management, and IIoT system management. This variety of use cases is made possible due to blockchain's ability to be integrated into customised information system architectures. Furthermore, the described sub-systems all utilise a cross-supply-chain unified database, enabling stakeholders such as designers, manufacturers, and assemblers, among others, to seamlessly share product information and thus collaborate more effectively. In addition to identifying the potential use cases and advantages of blockchain-based systems over conventional systems, the authors also highlighted a number of social and technical challenges associated with the implementation of blockchain technology into smart manufacturing systems. Social barriers mainly arise due to the implementation effort & cost, a lacking comprehension of the technology and its applications, missing upper-level management support, governmental regulation, and policies, as well as privacy concerns due to blockchain's transparency of information. Technical challenges accumulate around the consensus mechanisms and computing paradigms, which satisfy privacy protection needs, the scalability, efficiency, and performance of the system. Furthermore, future quantum-based attacks represent a major security threat to the cryptographic hash functions on which the blockchain architecture is based.

In [60], the authors present applications of blockchain technology towards a smart manufacturing system. The paper makes contributions towards implementing blockchains along the lifecycle management of products, including product design, product manufacturing, and product recycling. At the start of the product lifecycle, collaborative design practices are accelerated between professionals and customers by way of an unconfined, automated, yet secured communication and sharing of data. Furthermore, design documentation management processes can be enhanced by blockchain-inherent encryption algorithms, securing digital files and design documents. Independent designers may also benefit from an automated compensation and monetisation mechanism powered by smart contracts. Going further, the authors highlighted four applications of blockchains related to product manufacturing, presenting a decentralised procurement platform for raw materials with greater transaction traceability and accountability as well as automated settlement of procurement transactions. Manufacturing quality and equipment management, as well as inbound logistics, were also identified as key application areas for blockchain technology to introduce higher levels of automation, flexibility, enhanced security, and reduced waste and cost. Finally, some key application during the product recycling stage is presented, including the tracing of products by numerous stakeholders, which can enhance product recycling, remanufacturing, and reclamation efforts through improved data transparency. Triggering and executing a recall of defective products can furthermore be implemented through smart contracts, while blockchain's transparent architecture enables manufacturers to identify compromised quickly or faulty components and their associated suppliers.

[61] focuses on the conjunction of blockchain technology and additive manufacturing (AM) in the context of industry 4.0. The article aims to give answers regarding several challenges faced by the manufacturing industry in light of the ever-increasing demands of consumers for modern manufacturing. Following a thorough analysis of the current state, potentials and challenges of current-day additive manufacturing, the authors identified key use-case of blockchain technology within the AM industry. First,

blockchain can protect sensitive data and design files against unauthorised access, modification, replication, and distribution. Furthermore, the technology provides methods to license securely and enables new monetisation methods for the distribution of AM-related intellectual property, allowing for innovative, small-scale, and local companies to be competitive and profitable. Furthermore, the article describes how blockchains can be used to verify and authenticate data so that it can increase security within additive manufacturing processes, especially for critical industries like the military, government, and health care.

The paper by [62] focuses on 3D printing within the additive manufacturing segment, proposing a platform for the management of 3D-printed spare parts based on blockchain technology. The authors identify 3D printing's potential regarding spare parts due to the technology's capabilities, including real-time response manufacturing and design flexibility. The implementation of such a system is hindered by a missing secure and efficient data-sharing procedure as well as the incapability of current IT infrastructure to realise rapid products. Three key services of the proposed platform are advocated by the authors, which comprise a standard creation & collaboration service, a data sharing and management service, as well as a product traceability solution associated with the digital spare parts network. Said features cover the entire 3D printing value chain, providing improved security and accessibility of digital 3D printing data.

As described by [63], the term cloud manufacturing translates the principles used by cloud computing towards the manufacturing environment, enabling manufacturing-as-a-service (MaaS), with the goal of creating virtual production networks consisting of multiple manufacturers in order to increase production capabilities, flexibility, and efficiency. Next to state-of-the-art manufacturing facilities, with integrated IIoT and other industry 4.0-related systems, cloud manufacturing requires the use of secure, flexible, interoperable, and performant IT management systems.

The authors of [64] introduce a blockchain-based trust system, Blocktrust, for stakeholders within a cloud manufacturing network. The paper first points out that trust between provider and consumer can be defined as the key enabler for collaboration and, therefore, economic activity. This is especially important for small and medium-sized enterprises (SMEs), which cannot rely on an inherent trust associated with their brand name or reputation. Furthermore, since the Covid-19 pandemic, virtual inter- and intraorganizational interaction between entities have risen substantially, enabling more efficient business procedures; however, hindering the natural formation of trust between humans and, subsequently, enterprises. The proposed Blocktrust system is a peer-to-peer network based on a permissioned blockchain, which aims to provide the following three key services. First, it needs to give participants access to information, helping them distinguish between trustworthy and untrustworthy entities. Second, service providers and requesters need to be incentivised to act in a trustful manner. Third, bad actors need to be discouraged from using the platform. To archive these services, processes need to be implemented which generate computational trust. The authors have created a sophisticated system based on smart contracts which evaluate previous interactions of participants and give out corresponding trust and quality of service scores which are recorded on the blockchain to avoid manipulations and, in general, ensure decentralised storage, control, management, and distribution of associated data. This system represents a key opportunity for young companies without a track record to do business with computational trust.

The promise of a cloud manufacturing-as-a-service (CMaaS) platform has been attractive to customers, offering features such as instant pricing and access to a large spectrum of manufacturing facilities and capabilities. Current centralised approaches make compromises regarding transaction transparency and data-related shortcomings such as integrity, provenance and ownership of information, IP, and data. [65] introduces an architectural framework of a blockchain-based CMaaS platform, which is able to perform complex client projects such as mass customization of parts while being compatible with legacy software and hardware platforms, fully leveraging existing assets. Aided by its blockchain architecture, the system address above mentioned challenges of contemporary CMaaS systems, retaining data ownership and control with the client. Furthermore, it allows the tracing of digital assets through the system by modelling them as non-fungible assets (NFA).

In the context of new emerging manufacturing trends and technologies along the narrative of Industry 4.0, the authors of [66] describe the contemporary centralized networking approach as hindering the adoption of the above-mentioned innovations and especially cloud manufacturing. Lacking flexibility, efficiency, availability, and security are mentioned as the main challenges to overcome. To address said challenges, a blockchain-based peer-to-peer cloud manufacturing network, BCmfg, is presented. The main value proposition of the BCmfg system is the immutable data, accountability through transaction transparency, as well as system-wide encryption for data shared on the network, features which are based on the underlying blockchain framework. Furthermore, through the use of smart contracts, operational costs and inefficiencies can be reduced.

Cyber-physical systems

The term cyber-physical system (CPS) describes the connection between systems of the physical world and internet-based virtual cyberspaces. Low-fidelity CPS are already widely distributed throughout society, including internet-based navigation services like Google Maps or TomTom. Cyber-physical systems within the context of Industry 4.0 aim to interconnect manufacturing machines, systems, and tools through the internet, enabling the situational and context depended steering and management of resources and procedures, following advanced algorithms and AI systems, instead of blindly executing centrally commanded procedures [67].

In the work of [68], the authors investigate the application of blockchain technology within cyber-physical systems, addressing several challenges faced by current CPS implementation efforts. Mainly a lack of central control, restricted devices, lacking interoperability of nodes, network scale, data security and privacy threats are mentioned as challenges. Even though the authors identified blockchain's feature set as favourable, the implementation of a blockchain-based architecture for CPS has its own complications, including performance and scalability problems, high energy consumption and privacy issues, depending on the chosen blockchain architecture. In the paper, the authors develop several specific blockchain designs and mechanisms which deal with said issues. Furthermore, specific CPS industry applications are investigated, where challenges are matched with the previously developed blockchain design and mechanisms.

[69] presents a discussion around the implementation of blockchain technology within real-world cyber-physical production systems (CPPS). As CPPSs are highly complex architectures, hosting, integrating, and processing a large number of nodes, data and information, the authors see the implementation of a robust and performant computational platform as a requirement to implement a functional CPPS. To identify the potential of blockchain within this environment, the authors propose a CPPS architecture based on the technology. The presented system, BCPS, aims to address said challenges through its three-layer architecture. The connection net, the cyber net and the management net all have distinct features which help mitigate the implementation concerns of CPS in the manufacturing environment. The purpose of the connection net is to facilitate advanced connectivity and data management, integrity, and security.

The cyber net is designed to manage the interactions between cyber-cyber and cyber-physical entities as well as convert CPPS data into useful information. Lastly, the management net utilises the information gained from the cyber net to create a decision support system (DSS), enabling rapid decision capability as well as increased manufacturing productivity and sustainability.

Mass customised manufacturing (MCM)

One of the major expectations from the fourth industrial revolution, Industry 4.0, concerns the capability to mass produce and manufacture customised and personalised products. Facilitating this system, where consumers are able to request products from mass manufacturers according to their specific requirements and desires, requires a specific product design approach as well as the implementation of highly advanced physical systems, supply-chain infrastructures as well as suitable underlying information management systems [70].

The authors of [71] investigated blockchain's potential to serve MCM as an information technology, enabling an information management system suitable for the specific demands of MCM. The ability to handle and integrate diverse sources of information was characterised as blockchain's main advantage within manufacturing. Interoperability between different devices within and outside of an organisation was stated to be a defining factor regarding the usability of blockchain within a manufacturing network, requiring the design of new protocols and data structures. Furthermore, the development of improved and more efficient consensus mechanisms, as well as the use of permissioned blockchain architectures, were identified as requirements for the wider adoption of blockchain technology within manufacturing. Focusing on MCM, the authors indicated blockchain's key value proposition, namely, to move away from standard mass production information management systems like material requirements planning (MRP) and enterprise resource planning (ERP), which are not suitable for mass customised manufacturing. Instead, blockchain is flexible enough to utilize the dynamic capabilities of smart production systems and their computational capabilities. After identifying key opportunities and challenges, the paper proposes a conceptual design for the implementation of blockchain within an MCM context. By attaching the information of customer specifications to the product procurement, material and production data, the proposed blockchain-based information system can plan and coordinate the manufacturing system in an automated way to process the order.

Distribution of product

A less discussed area within the supply-chain academic field is the distribution of products to the consumer. As companies like Amazon in Europe and the United States or Alibaba in East Asia have mostly consolidated the digital marketplaces and B2C distribution for consumer products within their regions, many government officials, policymakers, and journalists increasingly criticise these companies for acting like monopolies and behaving anticompetitively towards smaller competitors [72]. For example, Amazon was accused of using the data gathered from its marketplace to develop its own products and placing them more favourably on its platform, stifling its competition [73].

Based on these circumstances, the work of [74] proposes a blockchain-based decentralised electronic marketplace. The author also identified the forming of monopolies by a single e-commerce corporation, controlling an entire section of the national economy. Within the decentralized marketplace and enabled by the blockchain, participants trade with each other directly and securely, giving no control towards a central authority. Furthermore, the proposed marketplace offers unaltered access to marketplace data, as inquired by the participant, preventing anti-competitive behaviour from any market player. Moreover, the blockchain-based architecture not only allows the circumvention of issues associated with centralised marketplaces but can offer new features and performance improvements, as stated by the author, including cost reduction and increased security of transactions, direct buyer-to-seller payments, as well as providing transactional anonymity and privacy if desired, reducing incentives for cyberattacks. In addition, blockchain's smart contracts ensure that buyers and sellers adhere to the predefined conditions of the transactions by automating the enforcement of said agreements.

Table 3: Potential of blockchain features on production & supply chain

Blockchain Feature & Type	Applications or use cases	Sources
Decentralised architecture and consensus mechanism	IC transaction management system, Sustainable manufacturing, Trust in cloud manufacturing, Cloud manufacturing as a service, Cloud manufacturing platform, Decentralized electronic marketplace	[57], [59], [64], [65], [66],[74]
Immutable storage & data security	Trust management system, Product lifecycle management, Interorganisational collaboration, Enhanced supply chain integrity, Smart manufacturing, 3D printing platform, Trust in cloud manufacturing, Cloud manufacturing platform, Enablement of Cyber-physical systems, Cyber physical production systems, Mass customized manufacturing, Decentralized electronic marketplace	[54],[55],[56],[58], [60], [62],[64], [66], [68],[69],[71], [74]
Transaction transparency & traceability	Trust management system, Interorganisational collaboration, IC transaction management system, Smart manufacturing, 3D printing platform, Trust in cloud manufacturing, Cloud manufacturing as a service, Cloud manufacturing platform, Decentralized electronic marketplace	[54], [56],[57], [60], [62], [64],[65], [66], [74]
Data as a property	Additive manufacturing, Cloud manufacturing as a service	[61],[65]
Dapps & smart contracts	Trust management system, Product lifecycle management, Interorganisational collaboration, Sustainable manufacturing, Smart manufacturing,	[54],[55],[56],[59], [60],[61],[64], [66], [69], [71],[74]

	Additive manufacturing, Trust in cloud manufacturing, Cloud manufacturing platform, Cyber physical production systems, Mass customized manufacturing, Decentralized electronic marketplace	
Incentive mechanisms & token economics	IC transaction management system, Smart manufacturing, Additive manufacturing, Decentralized electronic marketplace	[57], [60],[61], [74]
Permissionless blockchain	-	-
Permissioned blockchain	IC transaction management system, Enhanced supply chain integrity, Mass customized manufacturing	[57],[58],[71]

4.1.3 Circular economy & waste management

Waste management

As was identified in section 2.2.1, current waste management efforts, especially regarding the highly toxic and ecologically damaging electronic waste, have, in most countries, not yet been able to capture a satisfactory proportion of the total waste generated. This includes insufficient information management systems, which do not meet modern requirements regarding interoperability, a decentralised deployment approach, effective incentive mechanisms and automated process handling [75]. India has especially prominent waste and e-waste management issues, hence why the authors of [76] and [77] have proposed e-waste management systems for the Republic of India, which aim to leap-frog contemporary solutions.

The authors of [76] developed a theoretical blockchain-based e-waste management system which features a progressive approach, being designed from to start to consider both Forward Supply Chains (FSC) and Reverse Supply Chains (RSC), capturing the product's entire lifecycle. The FSC covers all activities related to the material procurement, production, and distribution of electronic products until they reach the consumer, involving critical stakeholders such as the producer, importer/exporter, wholesaler, and retailer. The RSC is concerned with the collection, sortation, refurbishment, or recycling of electronic products, which reached the end of its primary usage phase. Involved parties include e-waste collection centres, repair shops, and municipal solid waste (MSW), among others. With this approach, the aim of the authors is to create a system which considers all activities related to the products, considering all stakeholders from the beginning. Using smart contracts, holistic waste management processes are executed, including the registration of stakeholders and products, storage of supportive documents and metadata, product ownership transfer to other stakeholders, change of product state from usage phase to end of life, an incentive mechanism and payment channel to encourage stakeholder to adopted and utilise the system as designed and therefore increase the rate of reutilisation, recycling, and ecological disposal. As the authors suggest, the proposed system is highly dependent on several blockchain-specific features such as smart contracts, transaction transparency and traceability, as well as immutable storage and data security.

The paper of [77] features a similar proposal regarding the management of e-waste utilising a blockchain-based system architecture, aiming for an appropriate mechanism to collect, segregate and dispose of e-waste in an ecologically friendly way. First, the authors identify the need to supplement the centralised policy measures by the Indian government due to the current high share of unregulated stakeholders and the corresponding low policy compliance rate with a decentralised system, which directly incentivises participants to according to policy. Next, the authors defined key features of the system which are needed to reform the current waste management system, including blockchain-enabled book-keeping of electronic devices introduced into the market, allowing for the data-based formulation of e-waste collection targets and the subsequent rewarding or penalisation of responsible stakeholders, depending on if targets are met. Furthermore, consumers are incentivised to use smart contracts to dispose of their electronic waste through authorised channels and collection centres. The associated transactions between stakeholders can moreover be automated using smart contracts, allowing for higher process efficiency and accountability of stakeholders through the inherent traceability & transparency of blockchain-based transactions.

Table 4: Potential of blockchain features on circular economy & waste management

Blockchain Feature & Type	Applications or use cases	Sources
Decentralised architecture and consensus mechanism	Smart e-waste management	[77]
Immutable storage & data security	Forward and reverse supply chains for e-waste management	[76]
Transaction transparency & traceability	Forward and reverse supply chains for e-waste management, Smart e-waste management	[76],[77]
Data as a property	-	-
Dapps & smart contracts	Forward and reverse supply chains for e-waste management, Smart e-waste management	[76], [77]
Incentive mechanisms & token economics	Forward and reverse supply chains for e-waste management, Smart e-waste management	[76], [77]
Permissionless blockchain	Smart e-waste management	[77]
Permissioned blockchain	-	-

4.2 Results of multiple case study

In the following, the value of blockchain technology within design engineering is presented as demonstrated by early-stage applications by businesses and organisations. The results are sorted along the design engineering value stages.

4.2.1 Design & development

Bernstein.io – Intellectual property protection through immutable, timestamped recording of design and development processes.

The design & development value-creation stage has witnessed numerous major transformations in the last years and decades, with the emergence of digital design, simulation, and communication tools. An area which is seemingly still years behind is the protection and management of intellectual property (IP). As was discussed in section 4.1.1, blockchain technology is seen as a promising technology, enabling IP to enter the digital age while not compromising on security and privacy.

Bernstein [78] is translating this potential into a business case, providing clients with a blockchain-based tool to record the development and innovation process of products and services. The user can securely upload IP-relevant documents to Bernstein's web interface, where they are embedded within a blockchain transaction containing key information, including a cryptographic fingerprint of the IP documents, as well as proof of ownership.

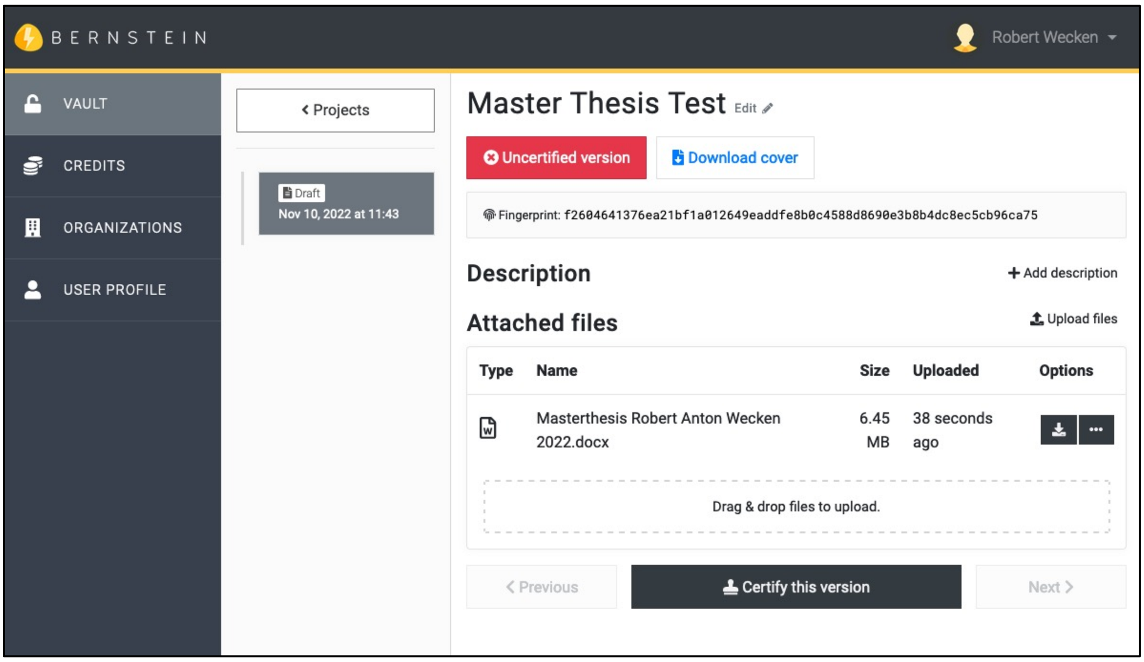


Figure 16: Bernstein.io web interface

By embedding it within the public Bitcoin blockchain, the transaction is immutably stored and timestamped, allowing it to be independently validated by anyone. In addition, future documents related to the same project or product can be subsequently linked to existing IP assets uploaded, thanks to the inherent blockchain architecture, creating a digital thread, unmistakably proving the project evolution, therefore making it a coherent development tool. Upon the user's request, the Bernstein web interface creates a certificate (see Figure 17) for any single or multiple IP asset(s) uploaded, which can be externally validated, even without the involvement of Bernstein.

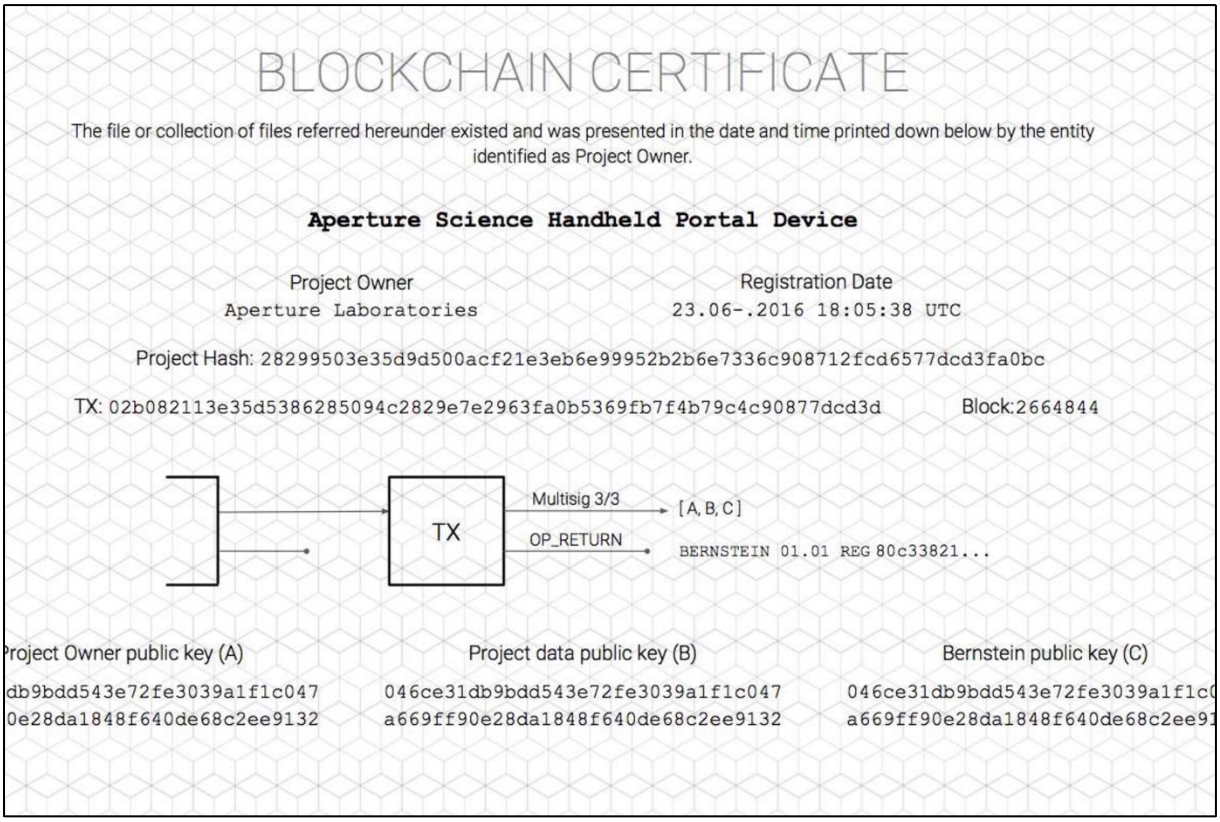


Figure 17: Blockchain certificate by Bernstein.io from [79]

The Bernstein developers addressed security and privacy concerns by encrypting the data uploaded so that IP assets are not disclosed, not even to Bernstein as the service provider. IP assets are only accessible with the private encryption key of the project owner [79].

Several use cases of the Bernstein platform were identified by the company, including protection and enforcement of trade secrets, securing IP in fashion and design, as well as enhanced contracts. The company claims that by creating a private trade secret inventory on the Bernstein web interface, clients can conveniently and privately notarise large quantities of trade secrets within their organisation, such as engineering data and specification, source code, digital prototypes, supplier and consumer information, or material composition data, fulfilling the formal requirements for trade secrets to be enforceable. As of today, recording the complex design process of various products, including consumer goods, furniture, and fashion, has been infeasible using contemporary IP legal protection tools like copyright and trademarks. Bernstein's blockchain-based platform enables designers to immutably record a timestamped digital version of their creative design and development process, empowering them to prove, defend, or enforce their intellectual property. The key value proposition of using a blockchain-based architecture is that the timeline of the value process is indisputable, making it strong evidence for legal processes and the court [80]. Lastly, Bernstein's platform provides clients access to blockchain-enhanced contracts. By supplementing legal contracts between the client and another legal entity with blockchain, the sensitive data involved can be handled in a secure and private manner through encryption. Furthermore, blockchain-enhanced contracts can refer directly to data of various kinds and formats, making them less ambiguous and subsequently improving their enforceability [81].

Spherity – Digital product passports (digital twin)

As discussed in section 4.1.1, future product information management is foreseen to be conducted entirely digitally through the so-called digital twin framework. Even policymakers, such as the European Union, are starting to mandate a unique data repository for certain individual products and components, such as batteries and electronic goods. The digital product passport (DPP) can be utilised by design engineers to permanently attach key information such as used materials, performance and durability data, recyclability, proof of responsible material sourcing and other lifecycle data to physical products. To fulfil its desired function, the DPP needs to be easily accessible, and its information needs to be verifiable by all involved stakeholders.

Spherity offers a blockchain-based digital product passport for products of various industries. The DPP by Spherity mainly acts as a compliance tool, facilitating the beforementioned legally required data repository of critical product information. This product-bound concentration of data is intended to raise product collection, recycling, and reuse rates at the end-of-life lifecycle stage. A secondary use-case of the DPP is to use it as an audit tool. Products and associated companies, which can take advantage of digital product passports, often require the independent examination of used processes, requirements, and guidelines to check if standards defined internally by the corporation itself or externally by governments are met. Internal audits are often conducted as a control mechanism to ensure that products meet the desired level of quality and to detect problems or inefficiencies within product development and the

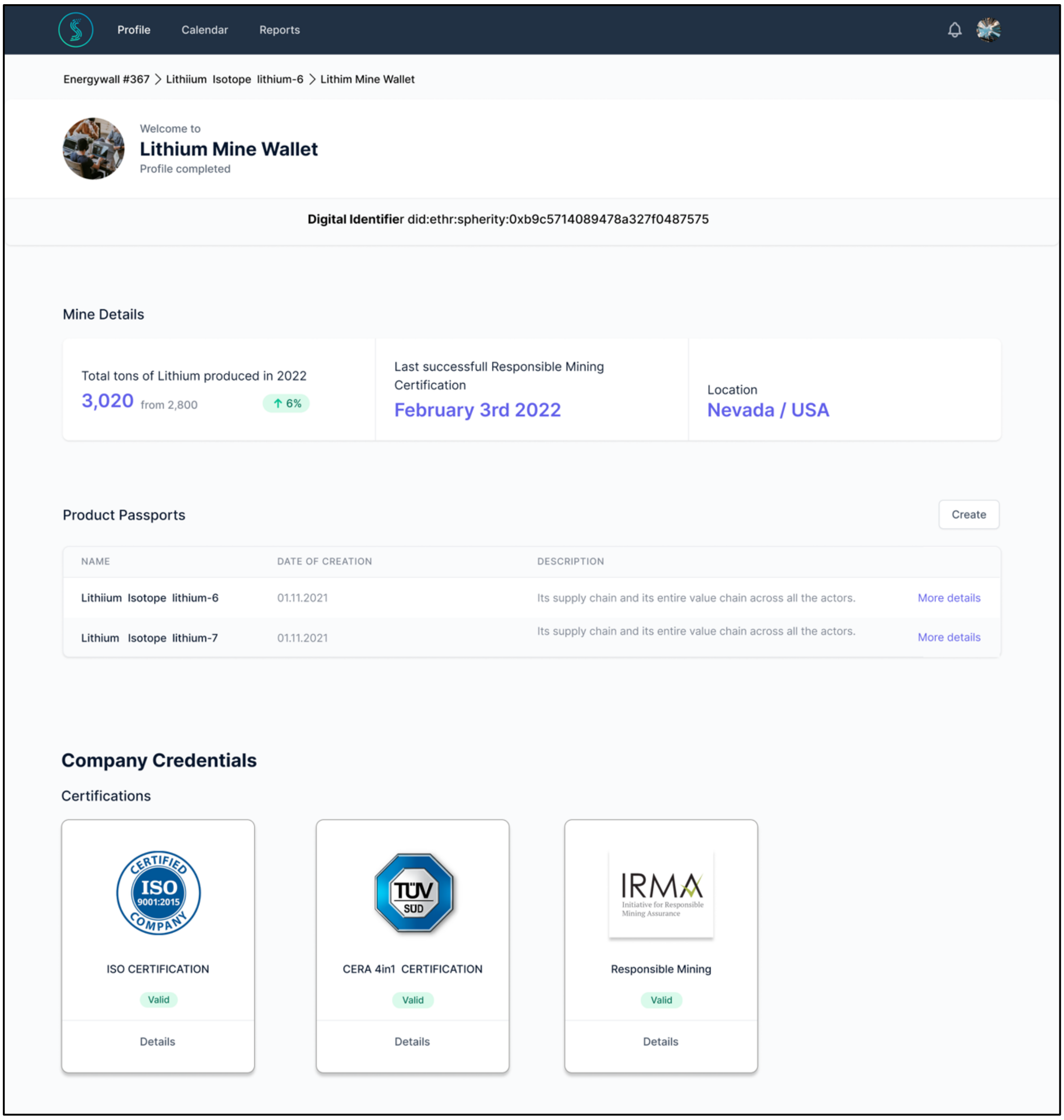


Figure 18: Digital product passport by Spherity

supply chain. During an audit, the DPP can provide access to verifiable information regarding the used materials and manufacturing conditions, increasing the audit process's efficiency and thoroughness by supplementing said information with complementary data such as recycling rates and real-time supply-chain procedures.

Alongside the above-mentioned implementation use cases, Spherity's DPP provides additional benefits and utility for involved stakeholders, including enhanced transparency about used raw materials and the production processes involved. This subsequently enables recyclers to make better and more ecologically friendly decisions and plan their operations more efficiently. Not only recyclers are enabled by the DPP to make better decisions, but users can also access the information on the digital product passport, which provides them insights regarding the sustainability of the product and used working conditions, like carbon footprint or fair-trade certification. This increase of transparency for the consumer incentives all entities of the value chain to act accordingly. Furthermore, DPPs by Spherity can be designed to intake information provided during the usage phase, which can then be used by design engineers to continuously optimise the products based on the actual usage behaviour of users [82].

4.2.2 Production & supply-chain

In section 2.2.1, the design engineering value stage production & supply chain was introduced alongside its characteristics, issues, and challenges. To overcome these challenges and to increase the efficiency and performance of the supply chains and production systems, the need for modern information management architecture, which ensures the robust, interoperable, secure, transparent, yet private exchange of information and data between entities of the value chain was identified. Furthermore, the inherent issue of trust between the participants involved hinders the execution of transactions and, therefore, the economic potential of said supply chains or production systems. Section 4.1.2 introduced several potential applications of blockchain technology, enabling advanced systems to manage supply-chain information & collaboration, set up cyber-physical systems, smart and cloud manufacturing systems, as well as new distribution models.

In this section, two case studies are presented, where the respective company or organisation took advantage of the unique opportunity to reinvent an entire section of the industry by creatively applying blockchain technology.

SAMPL – secure additive manufacturing platform

SAMPL is a smart manufacturing project by several partners from academia, including the Technical University of Hamburg (TUHH), Frauenhofer ENAS, and the University of Ulm, small and medium enterprises like 3D MicroPrint GmbH, PROSTEP AG, as well as larger corporations such as Airbus and Daimler [83]. The goal of the project is to develop a secure architecture for additive manufacturing based on blockchain technology. The architecture enables the securement of the entire additive manufacturing process chain, starting from the exchange of 3D CAD data between untrusted parties, the licensing of the printing operations, and the output on authorised 3D printers and component marking with RFID technology [84]. Investigating the process steps in detail, the user first uploads his printing files onto a secure, web-based exchange platform, where the receiver can be selected together with a predetermined number of printing licences. The conditions of the licensing agreement are permanently integrated into the printing file before being stored in the blockchain.

This procedure ensures the immutable recording of said transactions together with its associated printing details. Now the receiver can start printing the files in the predefined quantity recorded on the blockchain by using pre-authorised 3D printers, which must adhere to the printing conditions as recorded on the blockchain.

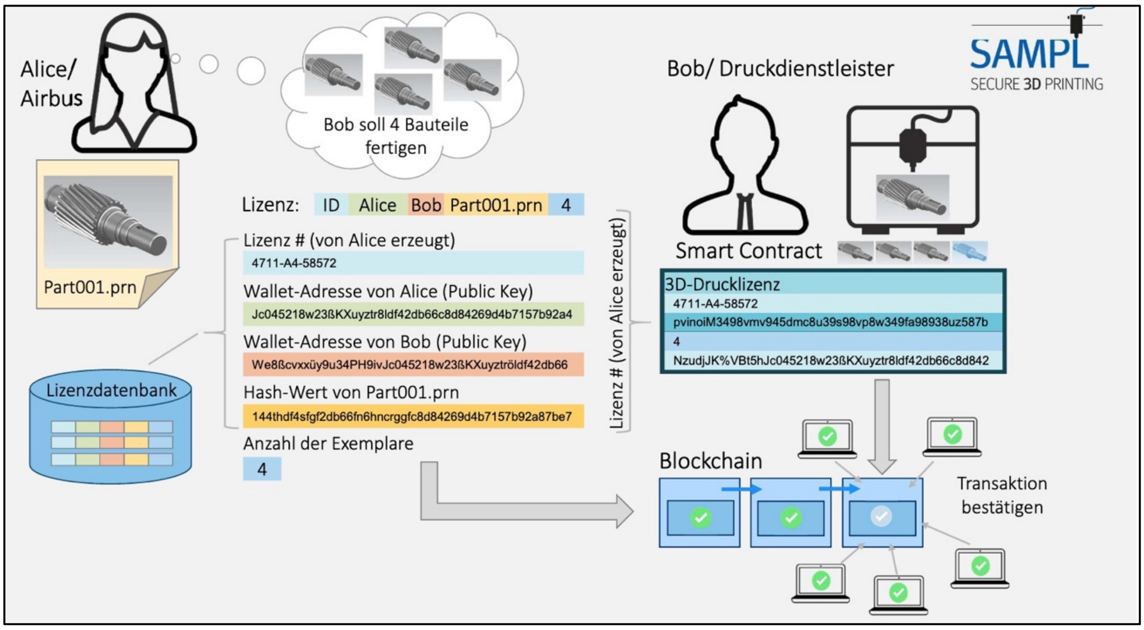


Figure 19: SAMPL transaction on the blockchain [92]

The special printers are represented on the blockchain as individuals' nodes so that they can trigger a transaction which marks the used licenses as used. Furthermore, the platform allows for the verification of produced parts by scanning the attached RFID tag and cross-checking the information with the data stored on the blockchain [85].

The main challenges associated with the development of a secure additive manufacturing platform are compliance with copyright and product liability laws alongside other legal details between actors. From a technical perspective, linking the authorised 3D printers and the blockchain was problematic but eventually resolved. The SAMPL platform can be utilised by many different industries in which additive manufacturing is used, but especially in sectors in which the demand for certified product and component quality and safety are high, SAMPL can bring a lot of value and higher process efficiency [85]. As was identified in section 4.1.2, the automotive, medical, defence and aeronautical industries are prime examples.

Minespider – supply chain transparency and traceability

Minespider is a young German/Swiss company aiming to build sustainable, carbon-neutral supply chains through enhanced transparency and traceability. The company offers several solutions for product manufacturers and mineral producers, which integrate into the Minespider platform. Mining and mineral producers can utilise Minespider to capture actively and subsequently communicate important information and datasets regarding their materials and involved processes. By making this information easily accessible to potential customers, mining and mineral clients of Minespider can differentiate from competitors, proving the sustainability of their products and actively complying with due diligence and ESG requirements. Information and data captured are managed through the Minespider platform and organised through their digital passport solutions, acting as a digital identity which contains provenance, ESG, carbon footprint and recycling data of the material. In this format, the information is easily communicable with relevant entities along the supply chain.

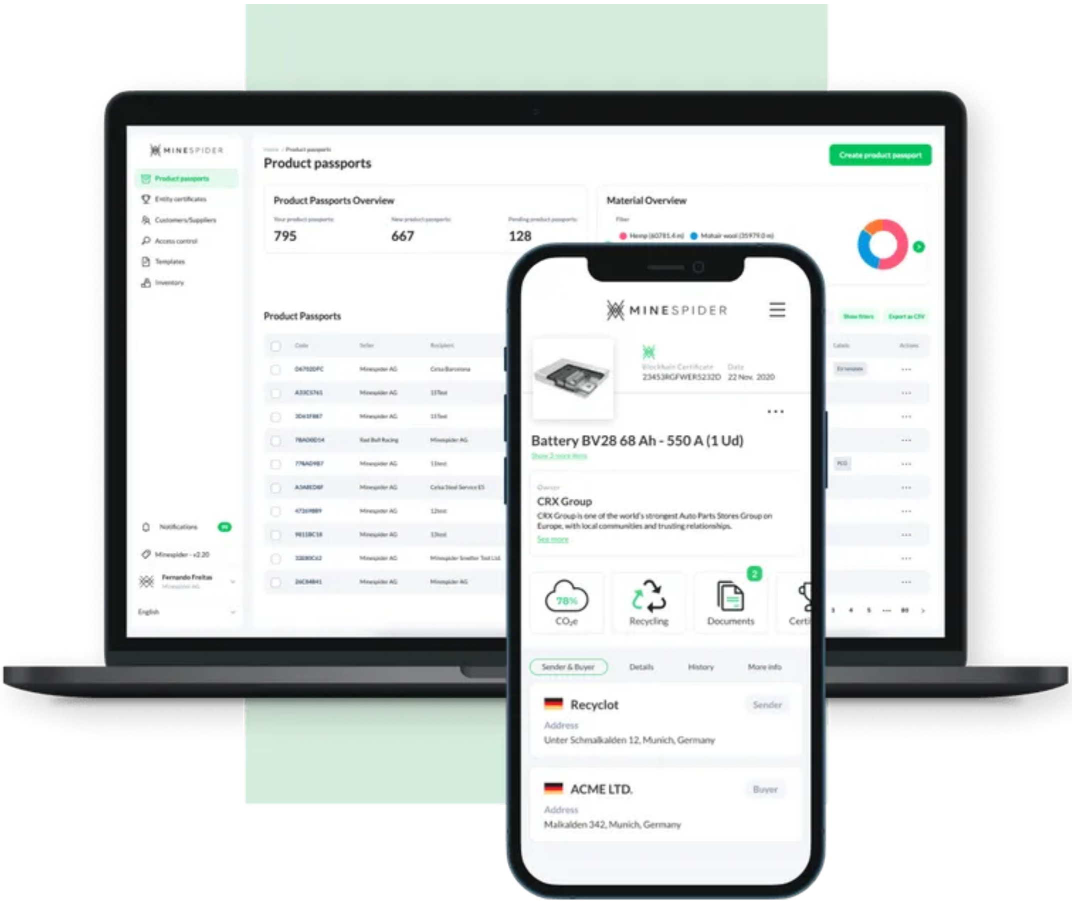


Figure 20: Minespider mobile and web platform [71]

Together with the physical material, its associated data also comes downstream in the supply chain to supplies and manufacturers in digital passport form. OEMs or product manufacturers can subsequently integrate the material digital passports into their digital product passports through the Minespider platform. The platform effectively acts as an information hub for clients to track used materials, create sustainability certifications and integrate new suppliers within Minespider [86]. To ensure data transparency, security, immutability, and traceability, the entire Minespider architecture is built on top of a consortium blockchain using a Proof of Authority (PoA) consensus mechanism, where members of the blockchain network must verify every transaction. By encrypting the data uploaded by supply chain participants on digital passports and storing the encryption key on the blockchain, the Minespider platform can ensure participants that the data within the digital passport has not been modified while preserving data privacy against unauthorised members of the network. This allows companies to exchange data securely through the computational trust created by the blockchain [87].

To validate their business and blockchain-based solutions, Minespider has published two client case studies. In 2019 the automotive OEM Volkswagen hired Minespider to bring material traceability and tracking functionality to their lead supply chain [88]. Due to the ecological degradation and compromised working conditions of local sites in developing countries, as well as lead's importance in the production of modern vehicle batteries and consumer electronics, the client saw the value of increasing supply-chain transparency and traceability to improve environmental and working conditions. Within the project, Minespider was able to support Volkswagen in identifying and mapping suppliers within their supply chains as well as assessing their sustainability and sustainability efforts and, lastly, showcase how the Minespider platform and technology can enhance many processes involved with supply chain transparency and traceability, making them more performant, interoperable, and efficient.

The second client case study covers the collaboration between Minespider and LuNa Smelter Ltd., a leading tin producer located in East Africa [89]. The aim of the project was to streamline the compliance processes of international due diligence initiatives, including the EU Conflict Minerals Regulation, Responsible Minerals Initiative (RMI), and the OECD due diligence guidance for a responsible supply chain of minerals. By vertically integrating many of the challenging production processes associated with the production and refinement of tin, LuNa Smelter differentiates itself and takes control of its ecological impact and the working conditions of the workers involved.

With this foundation, the company plans to use blockchain technology to attach production information directly to the finished goods and shipments in a timestamped and immutable way, making the responsible material origin and processes transparent and traceable. Furthermore, through the Minespider platform, associated documents for shipping and customs can be directly generated. In summary, the collaboration between Minespider and LuNa Smelter resulted in the digitisation of compliance-related processes hosted on the blockchain and directly linked to the physical goods, also resulting in increased compliance efficiency with the beforementioned organisations. As second-order effects, a strengthened brand image and improved client relationships can be reported.

4.2.3 Circular economy & waste management

In section 2.2.1, the circular economy & waste management design engineering value stage was introduced alongside its characteristics, issues, and challenges. This stage of the value chain is especially interconnected with all previous stages, with the clear ambition to minimise the number of resources extracted from the natural environment through reusing materials and energy within a circular system and thus also minimising waste.

In this section, the results of the case study of two companies are presented; both aim to provide holistic solutions for different stakeholders within the circular economy to maximise the effectiveness of their efforts by integrating their systems or solutions along the entire value chain.

Circularise – using blockchain technology to enable a circular economy at scale

Circularise offers clients software solutions to increase the traceability of their products and used materials, making key data like material or component origin, carbon footprint and associated certificates transparent and thus enabling involved stakeholders to make more sustainable decisions towards a circular economy. Circularise's software solutions are based on a decentralised, blockchain-based platform acting as a communication and data storage medium. Members of the platform are enabled to exchange and transact privately, disclosing only the exact amount of information to the intended receiver. By using blockchain, this functionality can be offered while also ensuring accountability so as not to encourage bad actors [90].

To demonstrate and test its software solution, Circularise partnered with the automotive OEM Porsche to bring greater visibility and traceability into a number of their component supply chains. Modern cars consist of up to 30.000 individual parts, making their value creation and supply chain extremely complex, with up to 20 supplier levels in a singular supply chain. Furthermore, the created parts and components consist of a vast number of different materials and material compositions from different origins across the globe, including various plastics, aluminium, fabrics, coatings, and adhesives. This situation makes obtaining accurate and trustworthy material and other critical data from all involved parts highly demanding and complicated.

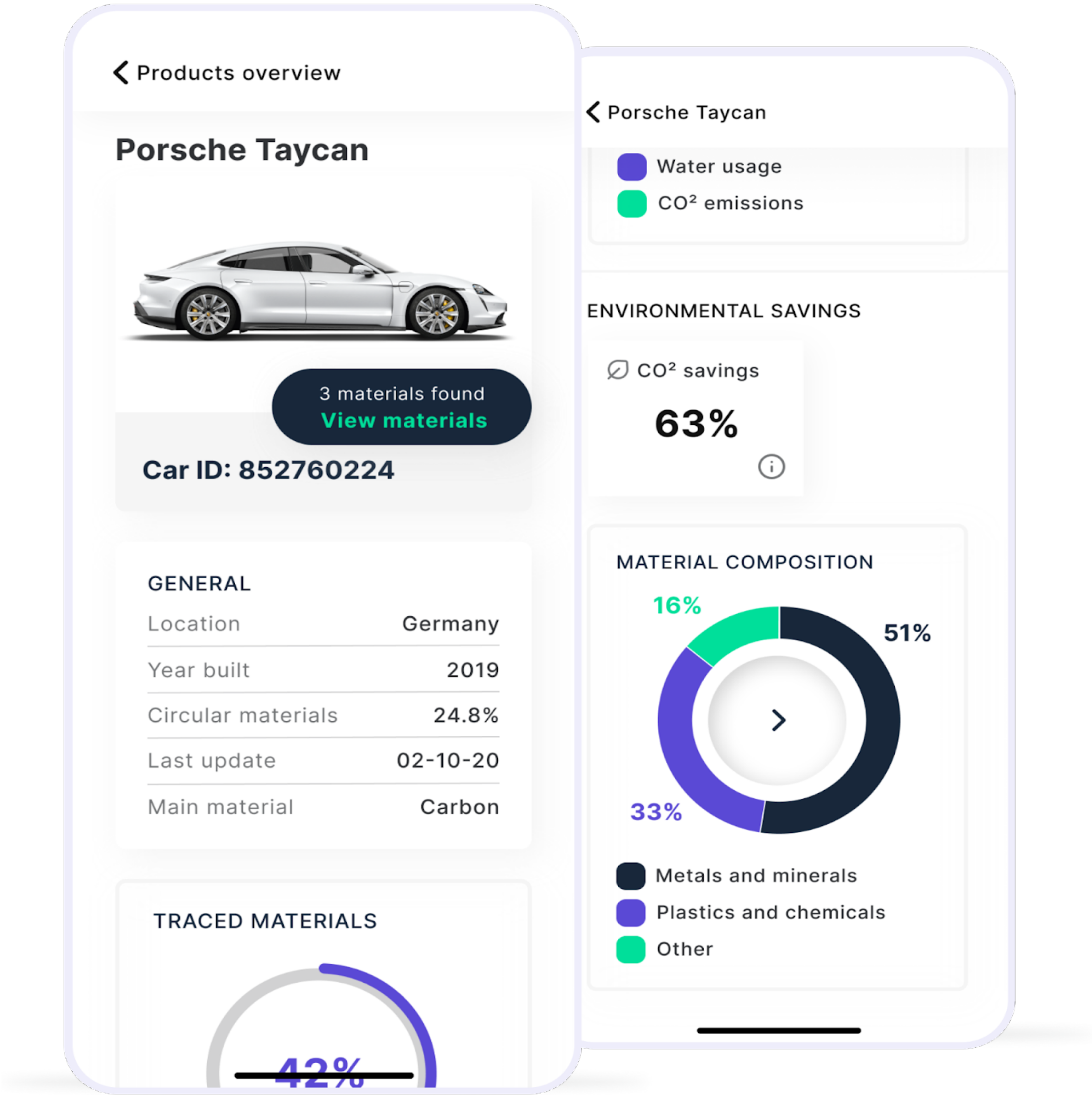


Figure 21: Product digital twin by Circularise

With Circularise's blockchain-based digital infrastructure, Porsche aims to integrate suppliers closer into their information management system while ensuring the confidentiality and ownership of sensible data of the respective supplier, enabling higher processes efficiency and performance. This higher integration of information is managed through Circularise's digital twin system, acting as a digital representation of physical materials and components, as discussed in section 4.1.1. These digital twins can be accessed by stakeholders through physical QR codes on the corresponding material batch or component. Furthermore, they are able to immutably link the material digital twin to the digital twin of the produced part, provided they have the required authority as granted by the system. Porsche and other clients are not the only profiteers of this blockchain-based system; consumers and recycling entities also benefit.

For example, responsible material manufacturers can gain the trust of customers by implementing the blockchain system in addition to verification by independent auditors to prove the accuracy of data implemented into the digital twin while still ensuring the confidentiality of their exact material compositions or other trade secrets. Consumers are empowered by the increase in information regarding the sustainability and labour conditions used for creating the product in question. Finally, stakeholders at the product's end of life, like recyclers, have access to trusted and accurate information regarding a product's used materials and recommended recycling processes, improving recycling efficiencies and recovery rates.

Everledger – battery repurposing and recycling

Founded in 2015, Everledger is a British company building a digital platform for clients to enhance their sustainability through increased transparency within upstream and downstream supply chains. The Everledger platform can be applied within numerous industries, including art, luxury goods, gemstones, fashion, and critical minerals; this case study focuses on their solutions within the battery sector to remain in the scope of the thesis. The blockchain-based battery passport solution by Everledger aims to meet the ever-increasing demands of sustainability-oriented customers as well as requirements by policymakers and other authorities. Manufacturers can create a unique digital identity/ digital twin of batteries (battery passport) on the blockchain to address critical areas for battery sustainability, namely battery material provenance certification and circular battery management.

With the Everledger platform, the manufacturers of batteries or products have the capability to onboard certified producers of critical materials used In battery production. The platform allows these approved entities in the supply chain to share compliance-related data securely with clients and regulators over the blockchain, ensuring an immutable transaction record while maintaining data privacy. This trusted transparency within the supply chain allows design engineers to select used materials and components from certified suppliers with confidence regarding their sustainability and ethical value creation. To manage the discarded batteries effectively, manufacturers have access to a specific web interface, where they are able to track the status of all associated batteries and modules which have been removed from vehicles, disassembled, or recycled. The web interface provides manufacturers with tools designed to track the entire fleet of batteries as well as observe individual batteries in detail. In addition to battery chemistry, exact material composition and component details, used manufacturing processes, the current state of health, serial number and associated certification and shipping documents, the battery passport also tracks the ownership journey and occurring processes of the battery from the manufacturer to final recycler immutably on the blockchain. This detailed record of the battery's life after the usage phase gives manufacturers and OEMs valuable insights regarding current recycling inefficiencies, helping them to design better and engineer the next generation of batteries and involved production and supply-chain processes.

Figure 22: Everledger battery digital passport

Approved recyclers also have access to a dedicated Everledger web interface, which is designed to act as a tool to record the recycling processes occurring to individual batteries and modules as well as give them critical information necessary for the proper execution of recycling activities. Due to the complexity of modern batteries, specialised recyclers are needed to conduct individual processing steps of recycling a battery. The Everledger platform accommodates this downstream supply chain arrangement and helps facilitate accurate communication between different recycling entities [90]. Through the blockchain-based architecture of the platform, sensitive data and trade secrets of the individual entities of the supply chain can be handled securely by making information only accessible to the intended receiver through the use of encryption [91].

5 Discussion and Conclusion

In this paper, two distinct methodologies were used to investigate and analyse the potential and value of blockchain technology in design engineering within consumer electronics. Before presenting the results of said methodologies in section 4, the paper covers critical background information on the associated topics in section 2, namely blockchain technology, design engineering, and consumer electronics. Section 3 presents the utilised research design and methodologies, supported by guiding visual elements. The following discussion of results in this section is structured according to the research framework shown in section 3.3, where the sub-research questions RQ1.1 and RQ1.2 are answered to represent and discuss the results of the systematic literature review and the multiple case study, respectively. Afterwards, the main research question, RQ1, is answered, combining the insights gained through both methodologies and the entire thesis. Last, the discussed results are reflected in a concluding statement.

Answer to sub-question 1.1

Before answering the research question RQ1.1, the results of the systematic literature review must be discussed. The research of this thesis found numerous proposed applications of blockchain technology by the scientific community within systems and information management architecture used for design engineering-related activities. Following the structure of the thesis framework of section 3.3, the proposed applications will be discussed along the defined value stages of design engineering. Within these value stages, a categorisation was conducted to further structure the proposals within similar application use cases.

Beginning with the value stage design & development, four application categories were identified. The first one, *product design against counterfeiting*, covers the works of three authors, who each present blockchain-based solutions to deter, prevent or detect illegally produced products or components, including specific solutions for smartphones and integrated circuits as well as more general approaches for products in general. An overarching theme detected among all three authors was the combination of blockchain with other complementary technology, pre-existing or specifically appended, to enhance the system's robustness, user-friendliness, and circumvent challenges associated with adopting BC. For example, to enhance the cloning prevention and traceability of integrated circuits, one author proposed the integration of physically unclonable functions within the circuit architecture, which can be used to permanently link individual IC to the blockchain by the original manufacturer.

This integration allows stakeholders along the supply chain to verify the authenticity of the components with confidence. This proposal exemplifies how BC implementation challenges, as mentioned in section 2.1.5, can be overcome by the strategic implementation of other technologies. Through these solutions, design engineers are empowered to design and develop consumer electronics which offer more robust anticounterfeiting and theft prevention capabilities.

The next application category, *digital twin*, includes two works proposing the use of blockchain to enable digital twin systems. DT allow for the constant, real-time monitoring of performance and reliability data and optimisation of systems and products, as described in detail in section 4.1.1. As digital twins require vast amounts of information from the physical world through numerous decentralised sensors and other monitoring systems, the implementation demands an appropriate data management architecture. The authors of the two works both present similar blockchain-based digital twin architectures, which aim to facilitate the secure, private transmission of data between physical nodes and virtual twins as well as the transaction of data between untrusted third parties. Through these architectures, an environment of confidentiality, integrity, and data availability is established, fostering economic growth through improved inter- and intraorganizational collaboration. However, the authors could have provided more evidence on how potential implementation challenges like performance and scalability could be resolved.

IP protection is the third category among the proposed design & development applications. One paper has first identified several challenges of the current international intellectual property protection system and subsequently identified blockchain features suitable to improve the system. Especially smart contracts, as a means of streamlining and automating registration processes and monetary transactions associated with intellectual property, are seen as promising. In addition, implementing digital assets as non-fungible tokens on the blockchain was presented as a way of enabling digital ownership and enhancing the economic handling of said assets like trading and monetisation. Independent professionals may also benefit from the improved monetisation capabilities offered through this blockchain application.

Lastly, one paper proposes an application of blockchain within the *product development process*. The authors created a framework based on blockchain to exchange and manage data across organisations. By taking advantage of blockchain's decentralised architecture, data immutability and transaction transparency, the framework allows secure, efficient, and interoperable cooperation between entities, allowing small and medium-sized enterprises to work better with large OEMs, making the value chain more inclusive. Furthermore, these blockchain features deliver increased accountability as every transaction can be traced back.

The application of blockchain within the design & development value stage has the potential to strengthen intellectual property protection, hinder the counterfeiting of products and components, enable advanced design and engineering tools, as well as foster inter- and intraorganizational communication and communication.

In the next value stage, production & supply chain, five distinct application categories were identified. The first five works contributed potential applications of blockchain within the *supply chain information & collaboration management*. Some proposed frameworks and architectures used blockchain technologies features to modernise and improve existing data management systems within and outside organisations such as PLM software. Through blockchain, these improved systems are designed to be more open and interoperable while ensuring the security and privacy of shared data. By sharing a common platform, this approach would also allow the reintegration of product data from the entire supply chain and reduce collaboration complexity between third parties. Going further, one author proposed an open framework where transactions between supply chain entities are monitored and evaluated to assign corresponding scores to participants, creating computational trust between entities and thus fostering business. Ensuring data accuracy and integrity were identified as critical challenges, which were overcome by procuring data from several trusted sources such as IIoT sensors and authorised entities. Another paper presented a potential solution for transactions within the integrated circuit industry. Currently, these suffer from malicious cyberattacks, threatening the intellectual property of manufacturers. A blockchain-based transaction platform secures data by encryption and transaction accountability, with smart contracts implemented to penalise and disincentivise bad actors.

Smart & cloud manufacturing systems is the next category under which six individual papers are represented. The overarching theme of the papers included in this category is blockchain's ability to support the next-generation manufacturing systems in line with the ambition of the fourth industrial revolution, Industry 4.0. A key ambition of these systems is to produce products that are more sustainable and ecologically friendly. Smart manufacturing enables the intelligent, efficient, and sometimes automatic sourcing and planning of resources, settlement of transactions, operation scheduling, and equipment management, among others. As described by the authors, blockchain technology has the potential to play a critical role in these manufacturing schemes by hosting the corresponding data systems necessary to manage and transfer data between actors. As both smart and cloud manufacturing systems are driven by the tight communication and collaboration of previously unassociated and, therefore, untrusted parties, blockchain features such as data security and privacy, transaction accountability, smart contracts, and token economics are exploited to make these systems feasible. However, the authors of several papers also pointed out some critical limitations of current blockchains, with system performance, scalability and data privacy being the most prominent. Two authors focused on blockchain's potential application within additive manufacturing or 3D printing industry. Since a higher percentage of the intellectual property associated with additive manufacturing is directly embedded in digital files, data security and integrity within a trusted environment are highly desirable. The authors state that blockchain technology can enable said environments while at the same time enhancing trading and monetisation processes. Cloud manufacturing aims to translate cloud computing principles towards manufacturing systems, enabling capabilities such as manufacturing-as-a-service (MaaS). CM requires secure, flexible, interoperable, and performant IT management systems, for which the authors propose blockchain as the best underlying IT infrastructure.

The works of two author groups can be categorised under the term *Cyber-physical systems*. As described in section 4.1.2, cyber-physical systems are systems defined by their connection between physical entities and internet-based cyberspaces. These systems are intended to connect industrial assets of various kinds, enabling the intelligent management of resources and processes associated with said assets. As a system with similar properties to the one discussed above, where a high number of untrusted nodes should interact within a decentralised network, the authors propose blockchain-based system management architectures, taking advantage of the same blockchain features, including data security. Again, blockchain´s performance and scalability issues were named as significant implementation challenges, alongside high energy consumption and privacy issues.

Another innovation within product production, *mass customised manufacturing*, is seen by the authors of one paper as a promising application of blockchain technology. MCM aims to offer clients and consumers personalised products efficiently produced in mass quantities. For this to occur, the authors saw the replacement of legacy manufacturing management systems like MRP and ERP as critical. Blockchain is proposed as an underlying framework for a management system where the computational abilities of context-aware smart manufacturing systems can dynamically control key operating processes and resource management.

Lastly, the authors of one paper exploited the potential application of blockchain within the last stage of the supply chain, the distribution of products. A decentralised electronic marketplace based on blockchain technology was conceptualised, which is meant to redistribute market control away from monopolies such as Amazon and Alibaba. As a decentralised platform, participants transact with each other directly, reducing costs and hindering anti-competitive behaviour. The use of blockchain further increases transaction security and allows for anonymous transactions. Smart contracts facilitate the execution of transaction agreements; however, it is yet to be seen how edge cases are handled where the unambiguous nature of code-based smart contracts cannot consider all possibilities.

In the final design engineering value stage, *circular economy & waste management*, two author groups present similar potential use cases of blockchain within the context of waste management. The ambition of both papers was to present a waste management solution which is able to collect as much electronic waste as possible by capturing detailed information along the entire value and supply chain. Through this approach, the blockchain-based system provides transparency and accountability for all involved stakeholders and their activities. Furthermore, token economics and smart contracts can be utilised to automate transactions between entities and incentivise sustainable behaviour of suppliers, manufacturers, distributors, users, and recyclers.

Now that the results of the systematic literature review have been discussed, a definitive answer to the research question **RQ1.1**, "*What potential applications of blockchain technology for design engineering are proposed by the scientific community?*" can be given.

A1.1: The scientific community has identified and proposed a large number of potential applications of blockchain technology within the value stages of design engineering, covering application areas such as anticounterfeiting, digital twin systems, IP protection, communication and collaboration within product development, supply chain information management, smart and cloud manufacturing, cyber-physical systems, mass customised manufacturing, product distribution and waste management. Within these, the role of blockchain can be described as an enabler. As described in section 2.1.1, blockchains are, from a technical perspective, an alternative to centrally operated databases. By themselves, the described features of this new type of database may seem relatively inconsequential; however, they allow systems and, subsequently, applications to be designed and constructed in fundamentally new ways, rearranging control and ownership of data as well as introducing incentive and monetisation mechanism able to influence user behaviour in significant ways.

Answer to sub-question 1.2

Similar to the process of answering the first research question, this section begins with a discussion of the results of the multiple case study presented in section 4.2 before answering research question RQ1.2. As described in section 3.5, the multiple case study was used to supplement the science-based knowledge gained from the systematic literature review with empirical knowledge of businesses and organisations implementing blockchain technology with design engineering. Through this approach, the current-day practical value of the technology was comprehended. In the following, the results of the multiple case study are discussed along the value stages of design engineering, with two cases representing each stage.

The first company represented in the design & development value stage, Bernstein, utilises blockchain technology to provide clients with a new solution regarding the intellectual property protection of design and engineering assets. The company understood the need of clients from the design and fashion industry for a more comprehensive tool to protect their creative and intellectual work against infringement from competitors and counterfeiters. According to this need, Bernstein developed a blockchain-based platform for users to upload design and development-related documents and data throughout the entire process of the project. Through blockchain integration, the development process is recorded in an immutable, private, and timestamped manner so that the client can, if required, unmistakably prove the project's evolution to legal entities. With this tool, Bernstein is aiming to make the protection of a client's development process feasible again. In a time of ever-increasing digitalisation, product complexity, and economic loss due to counterfeiting, contemporary IP protection tools are highly relevant to also protect the significant financial investment associated. Bernstein, however, has yet to prove the performance and scalability of its blockchain-based platform in order to be compatible with larger-scale organisations. The German start-up Spherity has developed a digital product passport (DPP) solution for manufacturers of various industries to represent physical goods in digital systems and gather data from the entire supply chain in a singular space. This digital passport approach helps enterprises develop products which are compliances and regulations orientated by immutably linking physical products to the required certifications and regulatory documents. Furthermore, the DPP allows for data collection even after production, which can inform the associated design engineers of the usage and recycling behaviour of the products. This information enables them to make better decisions regarding future product performance, quality, and usability, as well as their reusage, repair and recycling friendliness. Even though Spherity has published a high quantity of information regarding their solution, implementation case studies or external validation is still missing, so the actual value of their product to clients cannot be fully assessed at this time.

SMAPL, short for secure additive manufacturing platform, is an industry-academia collaboration project within the smart manufacturing sector and therefore belongs to the production and supply chain value stage. Through building a manufacturing platform on the blockchain, the project partners were able to develop a secure additive manufacturing process chain from exchanging sensitive 3D printing files between untrusted parties to marking authentic components with RFID chips, linking them to the blockchain for validation purposes. By securing every process step of the value chain, the project participants paved the way for a fully integrated, interconnected, and trusted smart manufacturing facility capable of serving highly demanding sectors like the medical and aeronautical industries. Minespider offers a blockchain-based platform to help clients archive higher supply chain transparency and traceability. By integrating and authenticating all supply chain entities, including raw material producers, suppliers and component and product manufacturers on their platform, the critical data from all participants can be securely and immutably linked to an individual digital product passport of the final product or component. This transparent access to supply chain data enables material producers to differentiate from competitors while allowing manufacturers to procure materials and components according to desired ethical and sustainability standards. Furthermore, compliance with ESG requirements is simplified. To ensure adequate platform scalability and performance, the Minespider platform is built on a permission blockchain using a specific Proof-of-Authority consensus mechanism. It remains to be seen if the blockchain architecture can scale when utilised by a large number of clients within complex supply chains. Furthermore, the specific permission blockchain may suffer from data security and privacy risks and data integrity challenges, as discussed in section 2.1.5.

The last two cases presented focus on utilising blockchain technology to increase the circularity of products and materials and improve recycling efforts. The Dutch company Circularise aims to enable product stakeholders throughout the value chain, from the material supplier to the consumer and recycler, to make more sustainable procurement, purchasing and recycling-related decisions. This is achieved by making critical information, like material or component origin, carbon footprint and associated certificates, more transparent and accessible. The data and access rights are managed through a digital twin system, which is hosted on the permissionless Ethereum blockchain. As a decentralised system, the Ethereum blockchain also ensures that data is not hosted by a central authority, retaining control and ownership of data with the individual supply chain participants and fostering adoption and interoperability. The big challenge for Circularise is not, however, a technological one, but to ensure the integrity of data provided by the participants as well as enforcing fines upon infringement. Everledger is the last case in this discussion. The British company developed a blockchain-based digital passport solution specifically for the repurposing and recycling of batteries from electric vehicles and consumer electronics. This digital battery passport is implemented through the entire supply chain and tracks material and process properties by letting approved entities share ESG and compliance-related data immutably and securely. Through encryption, the data is only made accessible to the intended receivers so as to protect sensitive data and trade secrets from being breached. In addition to manufacturers, an authorised recycler can also access detailed and unit-specific information about the to-be-recycled batteries. Due to the variety and complexity of modern battery units and modules, accurate and specific data can significantly increase recycling rates and efficiencies. Again, data integrity and mass adoption represent the biggest challenges towards achieving the supply chain transparency necessary for this type of solution to provide value towards manufacturers, consumers, and recyclers.

Now that the results of the multiple case study have been discussed, a definitive answer to the research question RQ1.2: "*What blockchain-based design engineering solutions and systems exist within consumer electronic life-cycle stages, and what value do they provide?*" can be given.

A1.2: As identified by the multiple case study, the presented solutions and systems within design engineering are based on three distinct blockchain application styles. The three styles are digital twin or digital product passport, collaboration platform, and data storage platform. All examined cases used one of the three underlying blockchain application styles within their solution or system tailored to the specific problem or use case selected by the company or organisation. These use cases or problems include intellectual property protection, compliance with ESG regulations, securing additive manufacturing, supply chain transparency and traceability, enhancing product and material circularity, as well as improving recycling efficiency. Due to the limitations of desk research, distinguishing the actual from the promised value was, in some cases, challenging, especially since the assessed businesses and organisations are in most cases still young and in the process of developing their solutions and systems. Nevertheless, it can be said that blockchain is a highly promising technology, capable of building new solutions and systems to the complex and multifaceted problems and challenges present in design engineering. In most cases, blockchain-based systems or solutions are highly dependent on auxiliary technologies and system structures to extract the full value from blockchain technology.

Answer to main question 1

After discussing the results of both the systematic literature review and the multiple case study as well as answering the two corresponding sub-research questions RQ1.1 and RQ1.2 it is now possible to provide a comprehensive answer to the main research question, RQ1: "*What is the potential and the value of blockchain features within design engineering in the context of consumer electronics and their life-cycle stages?*".

A1: Fundamentally blockchain technology can be considered a new type of database with different features, characteristics, and trade-offs. Therefore, its potential and value are determined by if and how systems and subsequent solutions can take advantage of the described differences and features and overcome challenges. This thesis has found numerous potential applications proposed by the scientific community and existing applications providing real value to several businesses and organisations within design engineering. Blockchain technology's most commonly proposed and utilised features are transaction transparency, immutable storage, smart contract functionality and data security. These features are strategically exploited to build numerous systems and applications, many of which can be classified under the term Industry 4.0. Industrial sectors like the supply chain and production are becoming interconnected and digitally enabled, promising, among others, much-improved transparency, accountability, and regulatory compliance of complex supply chains as well as the intelligent and automated manufacturing of products and management of resources. In these systems, blockchain is proposed and, in some cases, already implemented as an underlying system architecture through which the relationship, transaction and terms of authority and control are defined. Modern blockchain systems can furthermore provide the automated handling of transactions, including the settlement of financial transfers. Applying blockchain technology to intellectual property protection and anticounterfeiting was suggested in scientific publishing and affirmed by solutions offered by businesses. Moreover, the potential of new blockchain-based collaborative and customised development production models between consumers and OEMs with a tighter, more direct integration of designers and engineers was conceived to serve the need for mass customised manufacturing. Lastly, the potential of blockchains architecture and feature set were identified to be favourable for electronics marketplaces and the management of electronic waste, recycling, and circular economy efforts in general.

Conclusion

The objective of this paper was to research blockchain's potential and value within design engineering in the context of consumer electronics and provide readers with a practical understanding of the technology's applicability towards issues, challenges and opportunities currently faced by participants of the design engineering value chain. The three core topics, blockchain, design engineering and consumer electronics, were introduced to establish a shared knowledge base, and their key concepts discussed. Next, the research design and methodologies were presented, providing an overview of the structure and execution of the thesis research. Finally, the research results were documented, discussed, and utilised to answer the initial research questions. It is now possible to reflect on and further contextualise said findings in open discourse.

The analysed sources, including scientific literature and industry cases, have demonstrated that blockchain technology is, in essence, still a type of database. Therefore, as often depicted in public media, it cannot be considered a stand-alone solution to the problems or challenges faced by systems, businesses, or entire sectors. However, the research provides evidence that blockchain is an enabling technology which has the potential to fundamentally restructure existing information and operations. For this to occur, blockchain-based systems have to be complemented with other context-specific technologies and non-technical systems to be operational and extract the value from their architecture and features.

This characteristic is prominent within Industry 4.0 systems, which have been identified within the thesis as one of the major application areas of blockchain. Managing highly complex facilities, machinery, supply chains and production processes requires robust, secure, flexible, and accountable information management systems, especially when considering the trends towards mass customisation of products, supply chain transparency and a less linear and more circular approach of using resources and energy. In addition to the requirements mentioned, this transition towards a more connected, transparent and circular economy requires tight integration and communication between all value chain stakeholders. Blockchain's decentralised architecture and data management characteristics were found suitable to enable this transition on the information management side.

In spite of the described potential, the implementation of blockchains is faced with several challenges. Currently, most applications and use cases are designed towards maximum performance and scalability, which is delivered by traditional databases like AWS and Microsoft Azure.

Especially public or permissionless blockchains suffer from orders of magnitude less transaction performance compared to centralised databases, hindering their mass adoption by industry applications.

Large IT corporations have shown to utilise this performance advantage to act as central authorities with maximum control. However, as can be seen in global politics, the current preference towards maximum performance and scalability may shift towards a more balanced approach in certain geographic regions, where different stakeholders increasingly demand a decentralised database architecture, data ownership, transaction privacy and transparency. The value of these blockchain features may not be evident during day-to-day operations, however, in edge cases or during cyberattacks, they may prove to be critical.

Readers, especially industry professionals, are advised to follow the rapid development of blockchain technology carefully. Even though its impact on design engineering can be considered as indirect, blockchain's future implementations and applications have the potential to reconfigure the roles and authority of stakeholders within the value chain. The global shift towards increased sustainability has effectively demonstrated society's ability to re-evaluate its priorities, embracing a circular approach towards materials, energy, and other resources. As the analysed sources demonstrate, blockchains can be critical assets in transitioning towards these newly configured solutions, systems, and businesses.

To conclude, the findings of this thesis advanced and contributed towards the applied science of blockchain technology, particularly within design engineering and consumer electronics. By systematically reviewing selected literature and studying industry cases, the thesis identified key blockchain features and architectural characteristics and subsequently analysed their specific potential and value within its applications.

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Abbreviation directory

AI	Artificial intelligence
AM	Additive manufacturing
AWS	Amazon Web Services
BC	Blockchain
CAD	Computer-aided design
CAM	Computer-aided manufacturing
CE	Consumer electronics
CPS	Cyber-physical Systems
CRUD	Create, Read/Retrieve, Update, Delete & Destroy
Dapps	Decentralized software applications
DLT	Distributed Ledger Technology
DPP	Digital product passport
DSS	Decision support system
DT	Digital Twin
E-waste	Electronic waste
ERP	Enterprise resource planning
FSC	Forward supply chain
GPT	General Purpose Technology
IC	Integrated circuit

IIoT	Industrial Internet of Things
IP	Intellectual Property
IP	Intellectual property
MaaS	Manufacturing as a Service
MCM	Mass customized manufacturing
MRP	Material requirements planning
MSW	Municipal solid waste
NFT	Non-fungible token
OEM	Original equipment manufacturer
PLM	Product lifecycle management
PoA	Proof-of-Authority
PoS	Proof-of-Stake
PoW	Proof-of-Work
PUF	Physically unclonable functions
RSC	Reverse supply chain
SLR	Systematic literature review
SME	Small and medium-sized enterprises
TCP/IP	Internet protocol
TPS	Transactions per second

Appendix

Appendix A – Systematic Literature Review

Due to scalability issues the Scopus selection stages one and two cannot be displayed in this format and thus are available upon request.

Table 5: Systematic literature review – Scopus selection stage 3

Score	Authors	Title	Year	Source title	Cited by	DOI
3	Leng J., Ruan G., Jiang P., Xu K., Liu Q., Zhou X., Liu C.	Blockchain-empowered sustainable manufacturing and product lifecycle management in industry 4.0: A survey	2020	Renewable and Sustainable Energy Reviews	125	10.1016/j.rser.2020.110112
3	Malik S., Dedeoglu V., Kanhere S.S., Jurdak R.	TrustChain: Trust management in blockchain and iot supported supply chains	2019	Proceedings - 2019 2nd IEEE International Conference on Blockchain, Blockchain 2019	123	10.1109/Blockchain.2019.00032
3	Nazmul Islam M.D., Kundu S.	Enabling IC traceability via blockchain pegged to embedded PUF	2019	ACM Transactions on Design Automation of Electronic Systems	34	10.1145/3315669
3	Sahoo S., Halder R.	Blockchain-Based Forward and Reverse Supply Chains for E-waste Management	2020	Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)	5	10.1007/978-3-030-63924-2_12
3	Chen S., Cai X., Wang X., Liu A., Lu Q., Xu X., Tao F.	Blockchain applications in PLM towards smart manufacturing	2022	International Journal of Advanced Manufacturing Technology	1	10.1007/s00170-021-07802-z
2	Liu X.L., Wang W.M., Guo H., Barenji A.V., Li Z., Huang G.Q.	Industrial blockchain based framework for product lifecycle management in industry 4.0	2020	Robotics and Computer-Integrated Manufacturing	75	10.1016/j.rcim.2019.101897
3	Huang S., Wang G., Yan Y., Fang X.	Blockchain-based data management for digital twin of product	2020	Journal of Manufacturing Systems	69	10.1016/j.jmsy.2020.01.009
3	Omar A.S., Basir O.	Smart Phone Anti-counterfeiting System Using a Decentralized Identity Management Framework	2019	2019 IEEE Canadian Conference of Electrical and Computer Engineering, CCECE 2019	5	10.1109/CCECE.2019.8861955
3	Putz B., Dietz M., Empl P., Pernul G.	EtherTwin: Blockchain-based Secure Digital Twin Information Management	2021	Information Processing and Management	45	10.1016/j.ipm.2020.102425
2	Barenji A.V., Guo H., Wang Y., Li Z., Rong Y.	Toward blockchain and fog computing collaborative design and manufacturing platform: Support customer view	2021	Robotics and Computer-Integrated Manufacturing	16	10.1016/j.rcim.2020.102043
2	Suhail S., Hussain R., Jurdak R., Hong C.S.	Trustworthy Digital Twins in the Industrial Internet of Things With Blockchain	2022	IEEE Internet Computing	10	10.1109/MIC.2021.3059320
2	Esmaeilian B., Sarkis J., Lewis K., Behdad S.	Blockchain for the future of sustainable supply chain management in Industry 4.0	2020	Resources, Conservation and Recycling	149	10.1016/j.resconrec.2020.105064
2	Ajwani-Ramchandani R., Figueira S., Torres de Oliveira R., Jha S., Ramchandani A., Schuricht L.	Towards a circular economy for packaging waste by using new technologies: The case of large multinationals in emerging economies	2021	Journal of Cleaner Production	25	10.1016/j.jclepro.2020.125139
2	Belhi A., Bouras A., Patel M.K., Aouni B.	Blockchains: A Conceptual Assessment from a Product Lifecycle Implementation Perspective	2020	IFIP Advances in Information and Communication Technology	4	10.1007/978-3-030-62807-9_46
2	Hasan A.S.M.T., Sabah S., Haque R.U., Daria A., Rasool A., Jiang Q.	Towards Convergence of IoT and Blockchain for Secure Supply Chain Transaction	2022	Symmetry	3	10.3390/sym14010064
2	Cai H., Tan Q.	Blockchain-based data control for complex product assembly collaboration process	2021	ACM International Conference Proceeding Series	0	10.1145/3488838.3488873
2	Dietz M., Putz B., Pernul G.	A distributed ledger approach to digital twin secure data sharing	2019	Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)	15	10.1007/978-3-030-22479-0_15
2	Poongodi M., Hamdi M., Vijayakumar	An Effective Electronic waste management solution based on	2020	2020 IEEE 3rd 5G World Forum, 5GWF 2020 - Conference Proceedings	21	10.1109/5GWF49715.2020.9221346

	V., Rawal B.S., Maode M.	Blockchain Smart Contract in 5G Communities				
2	Yousuf S., Svetinovic D.	Blockchain Technology in Supply Chain Management: Preliminary Study	2019	2019 6th International Conference on Internet of Things: Systems, Management and Security, IOTSMS 2019	7	10.1109/IOTSMS48152.2019.8939222
2	Kupriianov G.A., Solnitsev R.I.	On Software and Information Support for the Design and Operation of the Recycling Infrastructure	2021	Proceedings of 2021 24th International Conference on Soft Computing and Measurements, SCM 2021	0	10.1109/SCM52931.2021.9507188
2	George A., Newell A., Papakostas N.	Intellectual Property Protection and Security in Additive Manufacturing	2019	Advances in Transdisciplinary Engineering	0	10.3233/ATDE190042

Table 6: Systematic literature review - start-set

Score	Authors	Title	Year	Source title	Cited by	DOI
3	Leng J., Ruan G., Jiang P., Xu K., Liu Q., Zhou X., Liu C.	Blockchain-empowered sustainable manufacturing and product lifecycle management in industry 4.0: A survey	2020	Renewable and Sustainable Energy Reviews	125	10.1016/j.rser.2020.110112
3	Malik S., Dedeoglu V., Kanhere S.S., Jurdak R.	TrustChain: Trust management in blockchain and iot supported supply chains	2019	Proceedings - 2019 2nd IEEE International Conference on Blockchain, Blockchain 2019	123	10.1109/Blockchain.2019.00032
3	Nazmul Islam M.D., Kundu S.	Enabling IC traceability via blockchain pegged to embedded PUF	2019	ACM Transactions on Design Automation of Electronic Systems	34	10.1145/3315669
3	Sahoo S., Halder R.	Blockchain-Based Forward and Reverse Supply Chains for E-waste Management	2020	Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)	5	10.1007/978-3-030-63924-2_12
3	Chen S., Cai X., Wang X., Liu A., Lu Q., Xu X., Tao F.	Blockchain applications in PLM towards smart manufacturing	2022	International Journal of Advanced Manufacturing Technology	1	10.1007/s00170-021-07802-z
2	Liu X.L., Wang W.M., Guo H., Barenji A.V., Li Z., Huang G.Q.	Industrial blockchain based framework for product lifecycle management in industry 4.0	2020	Robotics and Computer-Integrated Manufacturing	75	10.1016/j.rcim.2019.101897
3	Huang S., Wang G., Yan Y., Fang X.	Blockchain-based data management for digital twin of product	2020	Journal of Manufacturing Systems	69	10.1016/j.jmsy.2020.01.009
3	Omar A.S., Basir O.	Smart Phone Anti-counterfeiting System Using a Decentralized Identity Management Framework	2019	2019 IEEE Canadian Conference of Electrical and Computer Engineering, CCECE 2019	5	10.1109/CCECE.2019.8861955
3	Putz B., Dietz M., Empl P., Pernul G.	EtherTwin: Blockchain-based Secure Digital Twin Information Management	2021	Information Processing and Management	45	10.1016/j.ipm.2020.102425

Due to scalability issues the snowball selection stages one and two cannot be displayed in this format and thus are available upon request.

Table 7: Systematic literature review – snowball selection stage 3

Start-set source	Score	Authors	Title	Year	Source title	Cited by	DOI
2	3	Vatankhah Barenji R.	A blockchain technology based trust system for cloud manufacturing	2022	Journal of Intelligent Manufacturing	7	10.1007/s10845-020-01735-2
2	3	Marathe N., Chung L., Hill T.	A Blockchain Implementation to Improve Collaboration Between Original Equipment Manufacturers (OEM) and Partnering Organizations	2022	Proceedings - 2022 IEEE International Conference on Services Computing, SCC 2022		10.1109/SCC55611.2022.00032
3	3	Ghimire T., Joshi A., Sen S., Kapruan C., Chadha U., Selvaraj S.K.	Blockchain in additive manufacturing processes: Recent trends & its future possibilities	2021	Materials Today: Proceedings	9	10.1016/j.matpr.2021.09.444
3	3	Bonnet S.,	Impact of blockchain and distributed ledger technology	2023	Computers in Industry		10.1016/j.compind.2022.103789

		Teutebe rg F.	for the management of the intellectual property life cycle: A multiple case study analysis				
3	3	Espinoza Pérez A.T., Rossit D.A., Tohmé F., Vásquez Ó.C.	Mass customized/personalized manufacturing in Industry 4.0 and blockchain: Research challenges, main problems, and the design of an information architecture	2022	Information Fusion	8	10.1016/j.inffus.2021.09.021
3	3	Papakos tas N., Newell A., Hargade n V.	A novel paradigm for managing the product development process utilising blockchain technology principles	2019	CIRP Annals	23	10.1016/j.cirp.2019.04.039
4	3	Subrama nian H.	Decentralized Blockchain-based electronic marketplaces	2018	Communications of the ACM	151	10.1145/3158333
6	3	Pan L., Wu Y., Zhou M., Yu F., Lu Z., Chen H.	Blockchain Based Transaction Management System for IC Industry	2021	ACM International Conference Proceeding Series		10.1145/3460537.3460539
8	3	Hasan M., Starly B.	Decentralized cloud manufacturing-as-a-service (CMaaS) platform architecture with configurable digital assets	2020	Journal of Manufacturing Systems	40	10.1016/j.jmsy.2020.05.017
1	3	Dedeogl u V., Dorri A., Jurdak R., Michelin R.A., Lunardi R.C., Kanhere S.S., Zorzo A.F.	A Journey in Applying Blockchain for Cyberphysical Systems	2020	2020 International Conference on COMmunication Systems and NETworkS, COMSNETS 2020	19	10.1109/COMSNETS48256.2020.9027487
2	3	Zhang S., Lin Z., Pan H.	Research on 3D printing platform of blockchain for digital spare parts management	2021	Journal of Physics: Conference Series		10.1088/1742-6596/1965/1/012028
2	3	Li Z., Barenji A.V., Huang G.Q.	Toward a blockchain cloud manufacturing system as a peer to peer distributed network platform	2018	Robotics and Computer-Integrated Manufacturing	171	10.1016/j.rcim.2018.05.011
3	3	Lee J., Azamfar M., Singh J.	A blockchain enabled Cyber-Physical System architecture for Industry 4.0 manufacturing systems	2019	Manufacturing Letters	127	10.1016/j.mfglet.2019.05.003
3	3	Xu X., Rahman F., Shakya B., Vassilev A., Forte D., Tehranip oor M.	Electronics supply chain integrity enabled by blockchain	2019	ACM Transactions on Design Automation of Electronic Systems	28	10.1145/3315571
3	3	Alzahran i N., Bulusu N.	Block-supply chain: A new anti-counterfeiting supply chain using NFC and blockchain	2018	CRYBLOCK 2018 - Proceedings of the 1st Workshop on Cryptocurrencies and Blockchains for Distributed Systems, Part of MobiSys 2018	70	10.1145/3211933.3211939
7	3	Gupta N., Bedi P.	E-waste Management Using Blockchain based Smart Contracts	2018	2018 International Conference on Advances in Computing, Communications and Informatics, ICACCI 2018	28	10.1109/ICACCI.2018.8554912
3	2	Song G., Lu Y., Feng H., Lin H., Zheng Y.	An implementation framework of blockchain-based hazardous waste transfer management system	2022	Environmental Science and Pollution Research	1	10.1007/s11356-021-17489-0
3	2	Dolgui A., Ivanov D., Potryasa ev S., Sokolov B., Ivanova M., Werner F.	Blockchain-oriented dynamic modelling of smart contract design and execution in the supply chain	2020	International Journal of Production Research	207	10.1080/00207543.2019.1627439
3	2	Leng J., Yan D., Liu Q.,	ManuChain: Combining Permissioned Blockchain with a Holistic Optimization Model as	2020	IEEE Transactions on Systems, Man, and Cybernetics: Systems	112	10.1109/TSMC.2019.2930418

		Xu K., Zhao J.L., Shi R., Wei L., Zhang D., Chen X.	Bi-Level Intelligence for Smart Manufacturing				
3	2	Lemeš S., Lemeš L.	Blockchain in distributed CAD environments	2019	New Technologies, Development and Application II	5	10.1007/978-3-030-18072-0_3
3	2	Lee J.-H., Pilkington M.	How the Blockchain Revolution Will Reshape the Consumer Electronics Industry [Future Directions]	2017	IEEE Consumer Electronics Magazine	100	10.1109/MCE.2017.2684916
7	2	Thada A., Kapur U.K., Gazali S., Sachdeva N., Shridevi S.	Custom Block Chain Based Cyber Physical System for Solid Waste Management	2019	Procedia Computer Science	4	10.1016/j.procs.2020.01.068
8	2	Son S., Kwon D., Lee J., Yu S., Jho N.-S., Park Y.	On the Design of a Privacy-Preserving Communication Scheme for Cloud-Based Digital Twin Environments Using Blockchain	2022	IEEE Access		10.1109/ACCESS.2022.3191414
1	2	Suhail S., Hussain R., Jurdak R., Hong C.S.	Trustworthy Digital Twins in the Industrial Internet of Things With Blockchain	2022	IEEE Internet Computing	11	10.1109/MIC.2021.3059320
1	2	Malik S., Kanhere S.S., Jurdak R.	ProductChain: Scalable blockchain framework to support provenance in supply chains	2018	NCA 2018 - 2018 IEEE 17th International Symposium on Network Computing and Applications	90	10.1109/NCA.2018.8548322
7	2	Ongena G., Smit K., Boksebeld J., Adams G., Roelofs Y., Ravesteijn P.	Blockchain-based smart contracts in waste management: A silver bullet?	2018	31st Bled eConference: Digital Transformation: Meeting the Challenges, BLED 2018	11	10.18690/978-961-286-170-4.23
2	2	Li Z., Liu L., Barenji A.V., Wang W.	Cloud-based Manufacturing Blockchain: Secure Knowledge Sharing for Injection Mould Redesign	2018	Procedia CIRP	46	10.1016/j.procir.2018.03.004
3	2	Tozanlı Ö., Kongar E., Gupta S.M.	Trade-in-to-upgrade as a marketing strategy in disassembly-to-order systems at the edge of blockchain technology	2020	International Journal of Production Research	38	10.1080/00207543.2020.1712489
7	2	Gopalakrishnan P., Ramaguru R.	Blockchain based waste management	2019	International Journal of Engineering and Advanced Technology	10	
1	2	Hussain M., Javed W., Hakeem O., Yousafzai A., Younas A., Awan M.J., Nobanee H., Zain A.M.	Blockchain-based IoT devices in supply chain management: A systematic literature review	2021	Sustainability (Switzerland)	44	10.3390/su13245646
1	2	Islam M., Rehmani M.H., Chen J.	Transparency-privacy Trade-off in Blockchain-Based Supply Chain in Industrial Internet of Things	2022	2021 IEEE 23rd International Conference on High Performance Computing and Communications, 7th International Conference on Data Science and Systems, 19th International Conference on Smart City and 7th International Conference on Dependability in Sensor, Cloud and Big Data Systems and Applications, HPCC-DSS-SmartCity-DependSys 2021		10.1109/HPCC-DSS-SmartCity-DependSys53884.2021.00174
2	2	Rejeb A., Rejeb K., Keogh	Barriers to Blockchain Adoption in the Circular Economy: A	2022	Sustainability (Switzerland)	6	10.3390/su14063611

		J.G., Zailani S.	Fuzzy Delphi and Best-Worst Approach				
3	2	Mukherjee S., Nagariya R., Baral M.M., Patel B.S., Chittipaka V., Rao K.S., Rao U.V.A.	Blockchain-based circular economy for achieving environmental sustainability in the Indian electronic MSMEs	2022	Management of Environmental Quality: An International Journal		10.1108/MEQ-03-2022-0045
9	2	Zhang A.	Graphical design based on digital twin and interaction generation	2022	Computers and Electrical Engineering		10.1016/j.compeleceng.2022.108367
8	2	Lo C.K., Chen C.H., Zhong R.Y.	A review of digital twin in product design and development	2021	Advanced Engineering Informatics	27	10.1016/j.aei.2021.101297
7	2	Dondjio I., Themistocleous M.	Blockchain Technology and Waste Management: A Systematic Literature Review	2022	Lecture Notes in Business Information Processing		10.1007/978-3-030-95947-0_14
8	2	Aguilar-Ramirez J.E., Marmolejo-Saucedo J.A., Rodriguez-Aguilar R.	Digital Twins and Blockchain: Empowering the Supply Chain	2022	Lecture Notes in Networks and Systems		10.1007/978-3-030-93247-3_44

Table 8: Systematic literature review - selected sources

Authors	Title	Year	Source title	Cited by	DOI
Malik S., Dedeoglu V., Kanhere S.S., Jurdak R.	TrustChain: Trust management in blockchain and iot supported supply chains	2019	Proceedings - 2019 2nd IEEE International Conference on Blockchain, Blockchain 2019	126	10.1109/Blockchain.2019.00032
Liu X.L., Wang W.M., Guo H., Barenji A.V., Li Z., Huang G.Q.	Industrial blockchain based framework for product lifecycle management in industry 4.0	2020	Robotics and Computer-Integrated Manufacturing	80	10.1016/j.rcim.2019.101897
Leng J., Ruan G., Jiang P., Xu K., Liu Q., Zhou X., Liu C.	Blockchain-empowered sustainable manufacturing and product lifecycle management in industry 4.0: A survey	2020	Renewable and Sustainable Energy Reviews	137	10.1016/j.rser.2020.110112
Chen S., Cai X., Wang X., Liu A., Lu Q., Xu X., Tao F.	Blockchain applications in PLM towards smart manufacturing	2022	International Journal of Advanced Manufacturing Technology	2	10.1007/s00170-021-07802-z
Omar A.S., Basir O.	Smart Phone Anti-counterfeiting System Using a Decentralized Identity Management Framework	2019	2019 IEEE Canadian Conference of Electrical and Computer Engineering, CCECE 2019	5	10.1109/CCECE.2019.8861955
Nazmul Islam M.D., Kundu S.	Enabling IC traceability via blockchain pegged to embedded PUF	2019	ACM Transactions on Design Automation of Electronic Systems	35	10.1145/3315669
Sahoo S., Halder R.	Blockchain-Based Forward and Reverse Supply Chains for E-waste Management	2020	Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)	6	10.1007/978-3-030-63924-2_12
Huang S., Wang G., Yan Y., Fang X.	Blockchain-based data management for digital twin of product	2020	Journal of Manufacturing Systems	72	10.1016/j.jmsy.2020.01.009
Putz B., Dietz M., Empl P., Pernul G.	EtherTwin: Blockchain-based Secure Digital Twin Information Management	2021	Information Processing and Management	51	10.1016/j.ipm.2020.102425
Vatankhah Barenji R.	A blockchain technology based trust system for cloud manufacturing	2022	Journal of Intelligent Manufacturing	7	10.1007/s10845-020-01735-2
Marathe N., Chung L., Hill T.	A Blockchain Implementation to Improve Collaboration Between Original Equipment Manufacturers (OEM) and Partnering Organizations	2022	Proceedings - 2022 IEEE International Conference on Services Computing, SCC 2022		10.1109/SCC55611.2022.00032
Ghimire T., Joshi A., Sen S., Kapruan C., Chadha U., Selvaraj S.K.	Blockchain in additive manufacturing processes: Recent trends & its future possibilities	2021	Materials Today: Proceedings	9	10.1016/j.matpr.2021.09.444
Bonnet S., Teuteberg F.	Impact of blockchain and distributed ledger technology for the management of the intellectual property life cycle: A multiple case study analysis	2023	Computers in Industry		10.1016/j.compind.2022.103789

Espinoza Pérez A.T., Rossit D.A., Tohmé F., Vásquez Ó.C.	Mass customized/personalized manufacturing in Industry 4.0 and blockchain: Research challenges, main problems, and the design of an information architecture	2022	Information Fusion	8	10.1016/j.inffus.2021.09.021
Papakostas N., Newell A., Hargaden V.	A novel paradigm for managing the product development process utilising blockchain technology principles	2019	CIRP Annals	23	10.1016/j.cirp.2019.04.039
Subramanian H.	Decentralized Blockchain-based electronic marketplaces	2018	Communications of the ACM	151	10.1145/3158333
Pan L., Wu Y., Zhou M., Yu F., Lu Z., Chen H.	Blockchain Based Transaction Management System for IC Industry	2021	ACM International Conference Proceeding Series		10.1145/3460537.3460539
Hasan M., Starly B.	Decentralized cloud manufacturing-as-a-service (CMaaS) platform architecture with configurable digital assets	2020	Journal of Manufacturing Systems	40	10.1016/j.jmsy.2020.05.017
Dedeoglu V., Dorri A., Jurdak R., Michelin R.A., Lunardi R.C., Kanhere S.S., Zorzo A.F.	A Journey in Applying Blockchain for Cyberphysical Systems	2020	2020 International Conference on COMmunication Systems and NETworkS, COMSNETS 2020	19	10.1109/COMSNETS48256.2020.9027487
Zhang S., Lin Z., Pan H.	Research on 3D printing platform of blockchain for digital spare parts management	2021	Journal of Physics: Conference Series		10.1088/1742-6596/1965/1/012028
Li Z., Barenji A.V., Huang G.Q.	Toward a blockchain cloud manufacturing system as a peer to peer distributed network platform	2018	Robotics and Computer-Integrated Manufacturing	171	10.1016/j.rcim.2018.05.011
Lee J., Azamfar M., Singh J.	A blockchain enabled Cyber-Physical System architecture for Industry 4.0 manufacturing systems	2019	Manufacturing Letters	127	10.1016/j.mfglet.2019.05.003
Xu X., Rahman F., Shakya B., Vassilev A., Forte D., Tehranipoor M.	Electronics supply chain integrity enabled by blockchain	2019	ACM Transactions on Design Automation of Electronic Systems	28	10.1145/3315571
Alzahrani N., Bulusu N.	Block-supply chain: A new anti-counterfeiting supply chain using NFC and blockchain	2018	CRYBLOCK 2018 - Proceedings of the 1st Workshop on Cryptocurrencies and Blockchains for Distributed Systems, Part of MobiSys 2018	70	10.1145/3211933.3211939
Gupta N., Bedi P.	E-waste Management Using Blockchain based Smart Contracts	2018	2018 International Conference on Advances in Computing, Communications and Informatics, ICACCI 2018	28	10.1109/ICACCI.2018.8554912

Appendix B – Multiple Case Study

The free version of the Golden database does not permit the export of dataset, therefore the selection stage one cannot be shown here, thus readers are asked to insert the search queries as presented in Figure 13, Figure 14, and Figure 15 to obtain the full dataset.

Table 9: Multiple case study - Design & development selection stage two and three

Stage	Score	Name	Industry	Website	Location	Source
Selection Stage 2						
	Moved	IOTA Foundation	Global Trade & Supply-Chain, Indusrial IoT	https://www.iota.org/solutions/industries	Germany	Golden
2	2	Bernstein	IP Protection	https://www.bernstein.io	France	Golden
2	2	Spherity	Digital Twin, Product Passport	https://www.spherity.com	Germany	Golden
2	2	CADChain	Secure CAD file mangement	https://cadchain.com/#about	Netherlands	Qualitive Competitor Search
2	2	333D Limited	NFT + 3D printing	https://333d.co/mint-it-print-it/	Australia	Qualitive Competitor Search
2	1	Accubits	IT-Services und IT-Consulting	https://accubits.com/services/blockchain/	USA	Golden
2	1	IdeaBlock	IP Protection	https://ideablock.io/deployment	USA	Golden
2	1	DeepSquare	Cloud Development	https://deepsquare.io	Switzerland	Qualitive Competitor Search
2	1	LICENS3D	IP Protection	http://www.licens3d.com	Spain	Qualitive Competitor Search
2	1	BlockScience	Systems Engineering	https://block.science	USA	Qualitive Competitor Search
Selection stage 3						
3	3	Bernstein	IP Protection	https://www.bernstein.io	France	Golden
3	3	Spherity	Digital Twin, Product Passport	https://www.spherity.com	Germany	Golden
3	2	CADChain	Secure CAD file mangement	https://cadchain.com/#about	Netherlands	Qualitive Competitor Search
3	2	333D Limited	NFT + 3D printing	https://333d.co/mint-it-print-it/	Australia	Qualitive Competitor Search

Table 10: Multiple case study - Production & supply chain selection stage two and three

Stage	Score	Name	Industry	Website	Location	Source
Selection Stage 2						
2	2	Vechain	Supply chain	https://www.veworld.com/aboutUs	China	Golden
2	2	SyncFab	Manufacturing	https://syncfab.com/manufacturing-blockchain/	USA	Golden
2	2	Minespider	Supply chain	https://www.minespider.com	Germany	Golden
2	2	IOTA Foundation	Supply Chain, Indusrial IoT	https://www.iota.org/solutions/industries	Germany	Golden (moved from Design & Development)
2	2	SAMPLE	Manufacturing	https://sampl.fks.tuhh.de/de/home.html	Germany	Qualitive Competitor Search

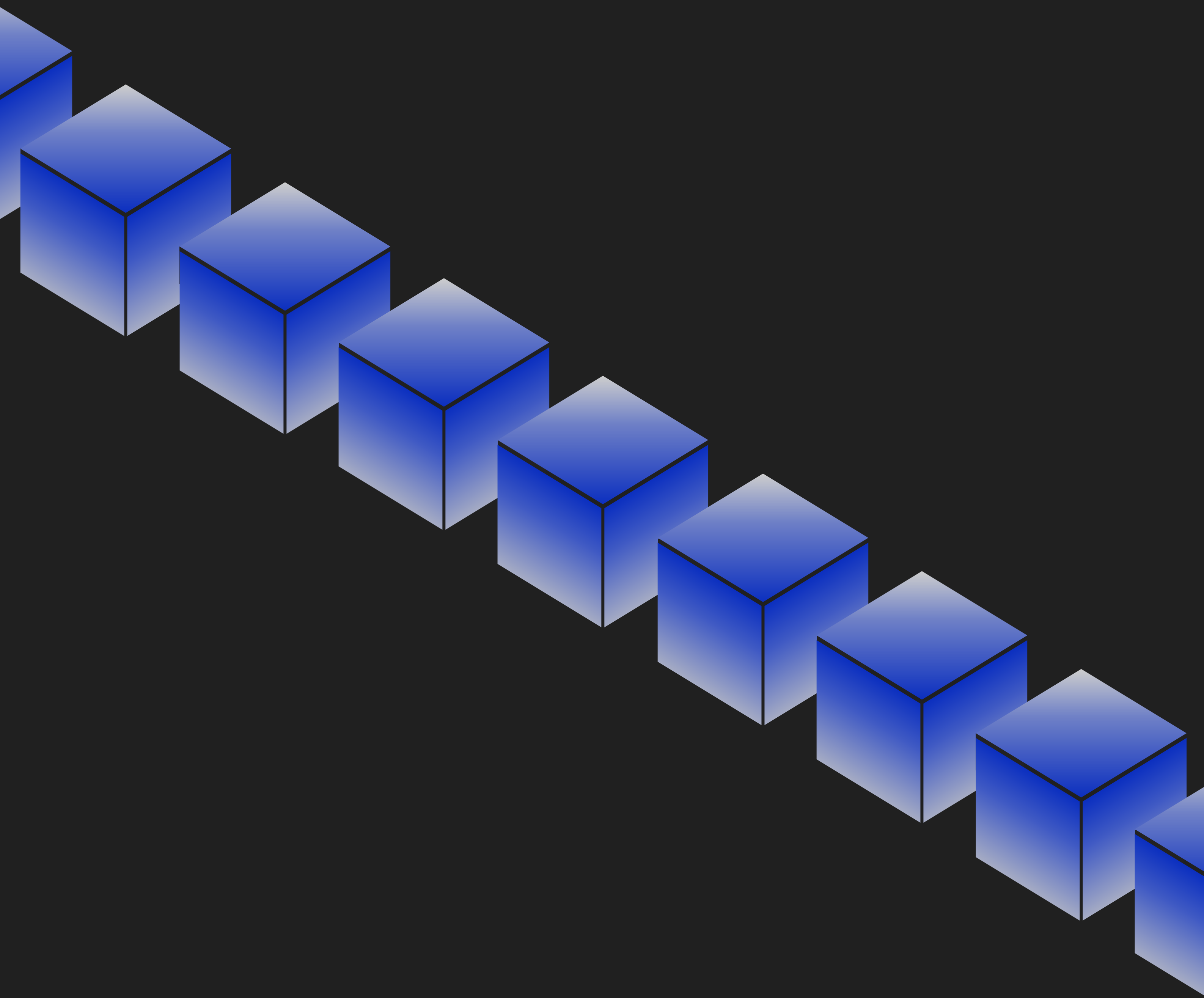
2	1	UBIRCH	Industry 4.0, Supply chain, Documentation	https://ubirch.com/de/	Germany	Golden
2	1	Everledger	Supply chain	https://everledger.io/about-us/	United Kingdom	Golden
2	1	Block Gemini	Supply chain	https://www.blockgemini.com	UAE	Golden
2	1	O4S	Supply chain	https://o4s.io	USA	Qualitive Competitor Search
2	1	Morpheus.Network	Supply chain	https://morpheus.network	USA	Golden
2	1	Waltonchain	Supply chain	https://www.waltonchain.org/#/en/wta/bluePaper	China	Golden
2	1	Knurls	Manufacturing	https://knurls.com	USA	Golden
2	1	Crystalchain	Supply chain	https://crystalchain.io/en/	France	Golden
2	1	Cubichain	Additive Manufacturing	http://www.cubichain.com		Golden
2	1	StaTwig	Supply Chain	https://statwig.com	India	Qualitive Competitor Search
2	1	Protokol	Manufacturing	https://www.protokol.com/industries/manufacturing-industry/	Netherlands	Qualitive Competitor Search
2	1	TradeLens	Supply chain	https://www.tradelens.com	USA	Qualitive Competitor Search
2	1	3DOS	Manufacturing	https://3dos.io	USA	Qualitive Competitor Search
Selection stage 3						
3	2	Vechain	Supply chain	https://www.veworld.com/aboutUs	China	Golden
3	2	SyncFab	Manufacturing	https://syncfab.com/manufacturing-blockchain/	USA	Golden
3	2	IOTA Foundation	Supply Chain, Indusrial IoT	https://www.iota.org/solutions/industries	Germany	Golden (moved from Design & Development)
3	3	Minespider	Supply chain	https://www.minespider.com	Germany	Golden
3	3	SAMPLE	Manufacturing	https://sampl.fks.tuhh.de/de/home.html	Germany	Qualitive Competitor Search

Table 11: Multiple case study - Circular economy & waste management selection stage two and three

Stage	Score	Name	Industry	Website	Location	Source
Selection stage 2						
2	2	Empower	Circular Economy	https://www.empower.eco	Norway	Golden
2	2	Circularise	Circular Economy	https://www.circularise.com/company	Netherlands	Golden
2	2	Plastiks	Waste collection	https://plastiks.io	Spain	Qualitive Competitor Search
2	2	Everledger	Circular Economy	https://everledger.io/industry-solutions/batteries/	United Kingdom	Qualitive Competitor Search
2	1	Recereum	Waste management	https://recereum.com	Ukraine	Golden
2	1	Recycllux	Recycling	https://recycllux.com	Romainia	Qualitive Competitor Search
2	1	Security Matters	Circular Economy	https://www.securitymattersltd.com	Australia	Qualitive Competitor Search
2	1	reciChain by BASF	Recycling	https://www.basf.com/ca/en/who-we-are/sustainability/Sustainability-in-Canada/reciChain.html	Canada	Qualitive Competitor Search
Selection stage 3						
3	3	Circularise	Circular Economy	https://www.circularise.com/company	Netherlands	Golden
3	3	Everledger	Circular Economy	https://everledger.io/industry-solutions/batteries/	United Kingdom	Qualitive Competitor Search
3	2	Empower	Circular Economy	https://www.empower.eco	Norway	Golden
3	2	Plastiks	Waste collection	https://plastiks.io	Spain	Qualitive Competitor Search

Table 12: Multiple case study - selected cases

Status	Name	Industry	Website	Location	Source
Selected	Bernstein	IP Protection	https://www.bernstein.io	France	Golden
Selected	Spherity	Digital Twin, Product Passport	https://www.spherity.com	Germany	Golden
Selected	Minespider	Supply chain	https://www.minespider.com	Germany	Golden
Selected	SAMPLE	Manufacturing	https://sampl.fks.tuhh.de/de/home.html	Germany	Qualitive Competitor Search
Selected	Circularise	Circular Economy	https://www.circularise.com/company	Netherlands	Golden
Selected	Everledger	Circular Economy	https://everledger.io/industry-solutions/batteries/	United Kingdom	Qualitive Competitor Search



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