Blockchain and Sustainability: A Systematic Mapping Study

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***Abstract*—Sustainability is a topic of increasing interest. The United Nations has released a list of 17 goals for sustainable development for the global community. Blockchain is a recent technological innovation that shows great promise in changing industries. In this paper, we look specifically at smart grids and supply chain management systems as areas where sustainable technological innovation can happen. To identify software engineering aspects of blockchain in smart grids and supply chain management, we start upon online libraries focusing on engineering and information technology, and we opted for the methodology of systematic mapping studies in software engineering. The search strategy identified 535 papers, of which 60 were identified as main studies for our mapping. To the best of the authors' knowledge, no previous similar studies exist. Results of the study show that the research connecting blockchain technology to smart grids and supply chain management systems is still young. None of the techniques or systems have yet been implemented in a real life setting. As such, more work has to be done before we can look at the actual implications of putting such technologies into use. Software engineering practices could prove to be very useful in the process of development. We propose that future studies can focus on bringing the technologies closer to real life implementations, as well as how to involve the end users in the development of the blockchain-based systems.**

***Index Terms*—blockchain, sustainability, green energy, supply chain management, smart grids, P2P energy trading, UN goals**

I. Introduction

With a growing focus on climate change and other environmental issue, there is also an increasing focus on sustainability. The United Nations (UN) has defined a list of goals for sustainable development, including issues ranging from food safety to green energy [17]. Blockchain technology can be a useful tool when trying to address certain issues with sustainable development.

In this paper, we conduct a systematic mapping study to discover how blockchain technology relates to sustainability, as defined by the UN goals. We defined the research questions 1) how is blockchain technology related to sustainability? 2) how can blockchain technology be used to develop sustainable technology?

Our research shows that there is an increasing amount of research into blockchain solutions that can be used to address sustainability. However, the solutions are still at relatively early stages of development. Nevertheless, the literature shows a careful optimism with regards to the possibilities of utilizing blockchain technology in the relevant fields.

The rest of the paper is organized as follows. Section II introduces the background and motivation of the study. Section III describes the methodology used. Section IV presents our findings. Discussion and conclusions are presented in Section V and Section VI respectively.

II. Background

The UN goals for sustainable development [17] [18] define 17 goals that the global community should work towards in order to achieve a sustainable future. Goals 2, 7 and 13 are *zero hunger*, *affordable and clean energy*, and *climate action* respectively, which are of particular interest to us. Goal 2 *zero hunger* claims that food waste and loss is a major issue, and part of that issue comes from the food items being spoiled during transportation or upon arrival. The food items can become spoiled because of inadequate storage facilities along the way, but it is difficult to know when or where that happened [3]. For goal 7 affordable and clean energy, it is imperative to make green energy production, e.g. solar panels, more widespread to reduce pollution from fossil fuel power generation methods. The more general goal 13 climate action calls for action to combat global climate change. One of the methods to do so that they point out is to use technological measures in a widespread manner, to reduce emissions where it is possible.

The second UN report is called the World Atlas of Illicit Trade [18] and describes how illegal goods are procured and sent around the globe, generating illegal revenue. In the Atlas, environmental crime is identified as the most profitable, as well as lowest risk, illegal operation, surpassing even drug trade in profitability. Environmental crime includes activities such as logging in protected forest areas such as in the Amazon. Part of the problem is the lack of control of where traded goods come from.

We identified blockchain technology as a possible candidate for making local, green energy production more widespread and for improving supply chain management. Blockchain is a distributed ledger technology, originally proposed as the backbone for the cryptocurrency Bitcoin, introduced in 2008 and launched in 2009. The blockchain technology could drastically change several industries and shows potential in several fields [19]. Taking a cursory look at existing literature, we identify the blockchain technology as a viable option [4] [16]. In this paper, we look at what has been done with regards to blockchain technology and implementations of smart grids and supply chain management systems, and how the literature has developed over time. We are particularly interested in software engineering related issues there.

However, blockchain technology is not without its drawbacks. Blockchain-based networks such as the Bitcoin network and the Ethereum network consume enormous amounts of energy [20] [12]. While the two networks themselves provide services that do not directly contribute to emissions, their footprint is huge.

III. Research Design

We opted for the methodology of systematic mapping studies in software engineering described by Petersen et al. [1] because it describes a systematic way to get an overview of state of the art, which is the primary goal of this paper.

A. Research Questions

TABLE I: Research questions.

Research Question	Explanation
1: How is blockchain technology related to sustainability?	The blockchain technology is being used for a variety of purposes. Some of the use cases might have a net positive effect on climate change, whereas others could cause significant harm.
2: How can blockchain technology be used to develop sustainable technology?	In which direction should further research and development of blockchain technology be headed?

The goal of this paper is to get an overview of what already exists in the literature, as well as see what is lacking and can be done in the future with regards to sustainable technology. So, two research questions are formulated, as shown in Table I. RQ1 relates to connecting the topics of blockchain technology and sustainability, and RQ2 looks at how the blockchain technology can be implemented to achieve sustainability.

B. Screening of Papers

An important step in searching for papers is to decide upon which libraries to use. Blockchain technology is primarily an IT innovation, with physical engineering, financial aspects and other fields coming into the picture after a programming solution has been created. As such, we consider software engineering to be the most relevant here. Taking into consideration that we are interested in the software engineering aspects of smart grids and supply chain management, rather than the economic or purely physical engineering, we decided upon online libraries focusing on engineering and information technology. We searched the libraries IEEE Xplore, ACM Digital Library and DBLP Computer Science bibliography and decided to use the sources available to our university. The libraries were decided upon by looking at possible candidates and doing cursory searches to scan for relevant results.

Initial test searches using the terms ”blockchain AND sustainability” and ”blockchain AND (sustainability OR sustainable)” yielded a very wide spectrum of results. To get more specific results, we decided to use more specific terms. We wanted to look more into certain use cases for blockchain technology, namely smart grids and supply chains, as we believe those to have the potential to improve the sustainability in industries. We wanted to look into green energy production and how to verify the green or sustainable origin of a product, which leads to the inclusion of ”green energy” and ”green certificate. The term ”climate change” was included to look for papers specifically looking into that specific topic, as we would like to look into how these may or may not be related. The final search strings can be seen in Table II. As blockchain technology is still fairly novel, rapid changes can be expected in the literature, so we only looked at papers from the last five years, i.e. from 2014 to 2018.

TABLE II: Search strings.

Search strings
blockchain AND ”climate change”
(blockchain OR cryptocurrency OR bitcoin) AND (”climate change” OR green OR ”green energy”)
(blockchain OR bitcoin OR cryptocurrency) AND (climate OR green OR ”green certificate”)
blockchain AND ”supply chain”
(blockchain OR bitcoin OR cryptocurrency) AND (climate OR green OR ”green certificate”) AND (”supply chain”)

The searches yielded a total of 535 papers. We used the library software Mendeley to keep track of all the papers. Some of the documents found in the libraries were tables of content for conferences and similar and were automatically excluded by Mendeley simply because they’re not meant to be cited. As such, the working set included 486 papers. To exclude irrelevant papers, we first removed all the duplicates among the papers, leaving 318. To decide upon the remainder, we have to develop inclusion and exclusion criteria. The criteria used for this study are shown in Table III. After the process of screening the papers, 60 were left. The bibliography can be seen here.

C. Groupings

As we did not find any previous mapping studies on blockchain and sustainability, we were left with the task of deciding the groupings from scratch ourselves. We decided on the grouping by following these steps:

1) Choose a sample of the papers
2) Read the titles, abstracts, conclusions and keywords if included

TABLE III: Inclusion and exclusion criteria

Inclusion	Exclusion
Studies related to using Blockchain to address sustainability related issues	Study related to the already proven and accepted implementations of blockchain technology, such as cryptocurrencies
Studies related to improving the energy efficiency of Blockchain services	Studies related to addressing problems with Blockchain technology not related to sustainability
Studies looking at the impact of Blockchain technology	Studies related to offering a service through Blockchain that does not address an environment or climate related topic

3) If the paper fits an existing category, put it there. If not, create a new category
4) After finishing the sample papers, do the same with the rest of the papers
5) If there is a too big of an overlap between categories, get rid of those categories and return to step 2

The papers were put into the following categories, as shown in Table IV. The three categories are further divided into their own sub-groupings, which can be seen in tables V, VI, and VII. The research types and contribution types were taken from the paper on systematic mapping studies in software engineering by Petersen et al. work [1].

TABLE IV: Groupings

Knowledge area	What is the topic of the paper?
Contribution type	What was the output of the paper?
Research type	What kind of research was conducted?

TABLE V: Knowledge areas

Supply chain for visibility	Making supply chains more transparent to the actors involved, to keep track of each step along the way
Supply chain for security	Improving the resilience of supply chains against malicious actors, including counterfeit protection
Supply chain for quality	Improving supply chains to ensure the quality of the end product, reducing spoilage and product loss
P2P energy trading	How to make Peer-to-peer (P2P) energy trading available to the public
Energy trading security	Discussing the security of using smart grids, or P2P energy trading in general
Blockchain energy efficiency	Proposals to improve the energy efficiency of future blockchain implementations

TABLE VI: Contribution types, from Peterson et al. [1]

Contribution	Description
Tool	Papers proposing a tool to aid further development
Model/method	Papers introducing new models or methods for addressing a problem
Framework	Papers proposing frameworks for development
Survey	Papers presenting data on what already exists, but do not propose a solution in themselves
Ontology	Papers proposing an ontology for identifying and discussing issues
Testbed	Papers proposing a testbed to aid further development

D. *Knowledge areas*

After the first look, most of the categories were already as they are now, but a category named ”smart cities” was also included. We excluded this term because it is a very broad term, which makes limiting it only to the topics of interest to us would be too inaccurate. There was originally a category called ”smart grids”, which was renamed ”P2P energy trading”, as the latter was deemed more accurate. Not all of the papers on energy trading between individuals specifically refer to smart grids. However, the category ”smart grid security” was kept, as the cases where security was included did deal with smart grids. Similarly, ”smart grid security” was renamed ”energy trading security”, as the former was found to be too strict. The term ”smart grids” refers to a fairly specific scenario, where there is an off-grid network of automated energy trading. ”P2P energy trading” is more general, and can cover any kind of situation where individuals are trading energy between each other.

Overall the papers fell fairly neatly into the final knowledge areas. A small number of papers could potentially fit into more than one, and one falls slightly outside a strict categorization. The rest were not problematic. No papers trying to solve the energy issues of existing blockchain-based systems were found, which is reflected in the categories.

IV. Results

A. *RQ1 How is Blockchain technology related to sustainability?*

In this paper, we limited the scope of the huge topic of blockchain technology and sustainability, to the fields of smart grids and supply chains, while also looking at the energy expenditure of blockchain implementations. Smart grids were

TABLE VII: Research types, from Peterson et al. [1]

Research type	Description
Validation research	Techniques investigated are novel and have not yet been implemented in practice. Techniques used are for example experiments, i.e., work done in the lab.
Evaluation research	Techniques are implemented in practice and an evaluation of the technique is conducted. That means, it is shown how the technique is implemented in practice (solution implementation) and what are the consequences of the implementation in terms of benefits and drawbacks (implementation evaluation). This also includes identifying problems in the industry.
Solution proposal	A solution for a problem is proposed, the solution can be either novel or a significant extension of an existing technique. The potential benefits and the applicability of the solution are shown by a small example or a good line of argumentation.
Philosophical paper	These papers sketch a new way of looking at existing things by structuring the field in the form of a taxonomy or conceptual framework.
Opinion paper	These papers express the personal opinion of somebody whether a certain technique is good or bad, or how things should be done. They do not rely on related work and research methodologies.
Experience paper	Experience papers explain on what and how something has been done in practice. It has to be the personal experience of the author.

chosen, as we believe they can be helpful in working towards the UN goals for sustainability, and in creating the ”smart cities” of the future. We also included supply chains, to see if they can be used for proofs of origin and traceability, as we believe it can be an option to reduce environmental crime and food waste, as well as other use cases. Figure 1 shows that there has been a significant increase in publications, which looks into blockchain technology used in conjunction with smart grids or supply chain management systems, over the last two years. Figure 2 shows that validation research and solution proposals appear earlier than other types of studies. Validation research looks into proposing new possibilities for addressing a given problem. The papers try to prove the validity or viability of some new technique, without actually implementing it. Solution proposals take it one step further, trying to develop such techniques to a point where they would be suitable for implementation. The increased interest here can be seen as a growing initiative for solving these problems that have caught the public eye.

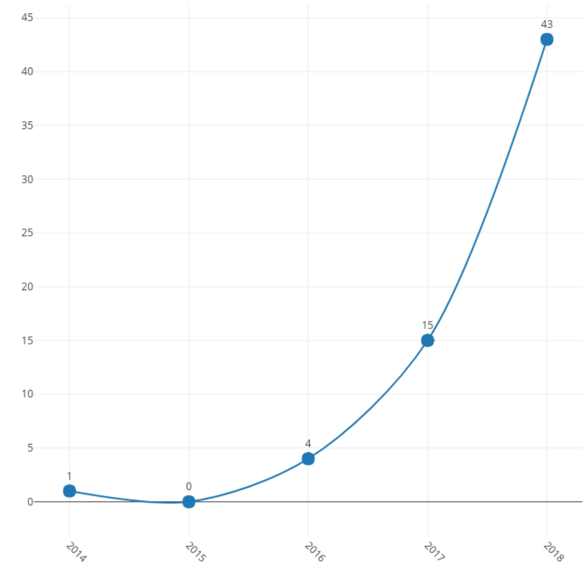

Fig. 1. Number of publications by publication year.

Figure 2 also shows the lack of evaluation research, which implies that researchers have not gotten so far as to implementing the proposed techniques in real life test scenarios. Figure 1 shows that there is very little research into the fields of blockchain and sustainability before 2018. It would be overly optimistic to expect full solutions to problems as big as these in such a short period of time. Some philosophical papers show up from 2018. It might be that there was a conventional understanding of how to utilize blockchain technology for sustainability, which went unquestioned. However, with growing interest comes growing criticism, which could explain why researchers are now trying to propose different ways of understanding and addressing the issues. The same arguments apply to opinion papers. There are almost no experience papers, hinting at just how new the field is and implying that not much has actually been tested in the real world.

B. RQ2 How can Blockchain technology be used to develop sustainable technology?

The number of solution proposals, validation papers and evaluation research makes it clear that there is a potential for utilizing blockchain technology in sustainable technology. Not all the research papers we discovered deal directly with sustainability. In fact, quite a few do not mention sustainability at all, some focusing instead on economic viability. However, economic viability is indeed an important factor for technology adoption. Technological innovation that costs more money than it saves will have a hard time becoming widespread.

As can be seen in Figure 4, we found many papers on P2P energy trading and security in smart grids. In all the papers, blockchain technology plays a central role. Hence, it

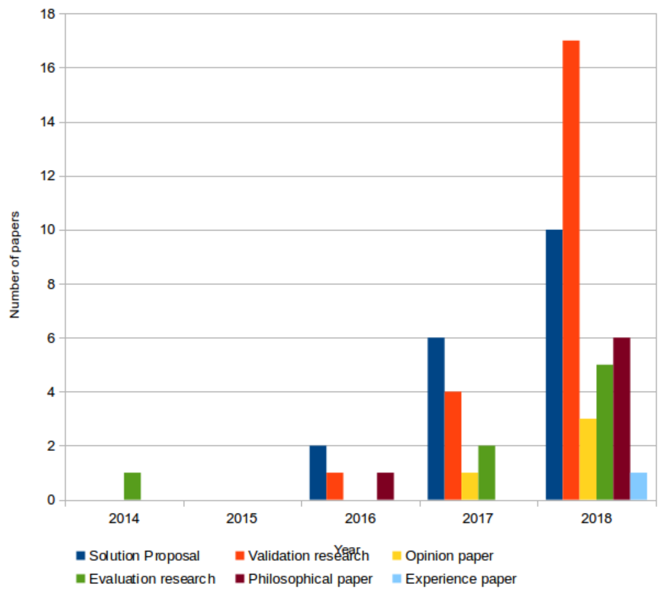

Fig. 2. Research type as frequency per year.

is obvious that researchers believe it is possible to impler these systems. The papers do not discuss whether it is doa but rather the specific details of implementation. We see s validation and evaluation research, a fair amount of solu proposals, and little else. Continuing the argument above, lack of real life tests can be seen as a sign that researchers still figuring out the best practices for how to implement smart grid systems.

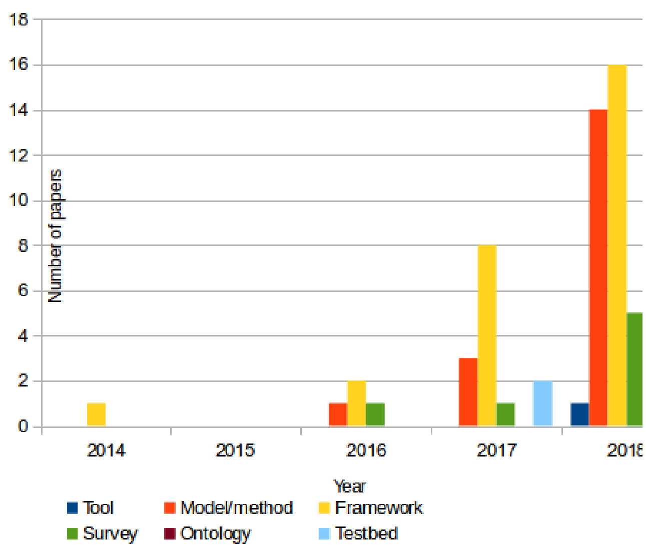

Fig. 3. Contribution type as frequency per year.

Looking at the contribution types in Figure 3, we can see that there are many framework proposals as well as models/methods. There is only one paper contributing a tool for further development. So researchers have proposed many available variations of implementations, but little on how to use these in real life. The two testbeds might prove useful in achieving that. As research progresses and the field matures, we will probably see more tools and testbeds, that will make further developments easier. In smart grids, ensuring consensus on how to implement grids might be crucial. As we are here dealing with infrastructure, compatible solutions can be important. If the solutions are not compatible, each grid will become a separate island, making further development, and perhaps connections over longer distances, much more difficult. Lombardi et al. claim that blockchain-based smart grids will have limited effects on the industry [16]. Their research shows that certain parts of the industry can be improved through the use of the new technology, such as reducing costs and simplifying transactions, but it will not be disruptive. Chitchyan and Murkin looked at more of the energy sector as a whole [11]. They "remain cautiously optimistic", but similarly do not expect a complete revolution.

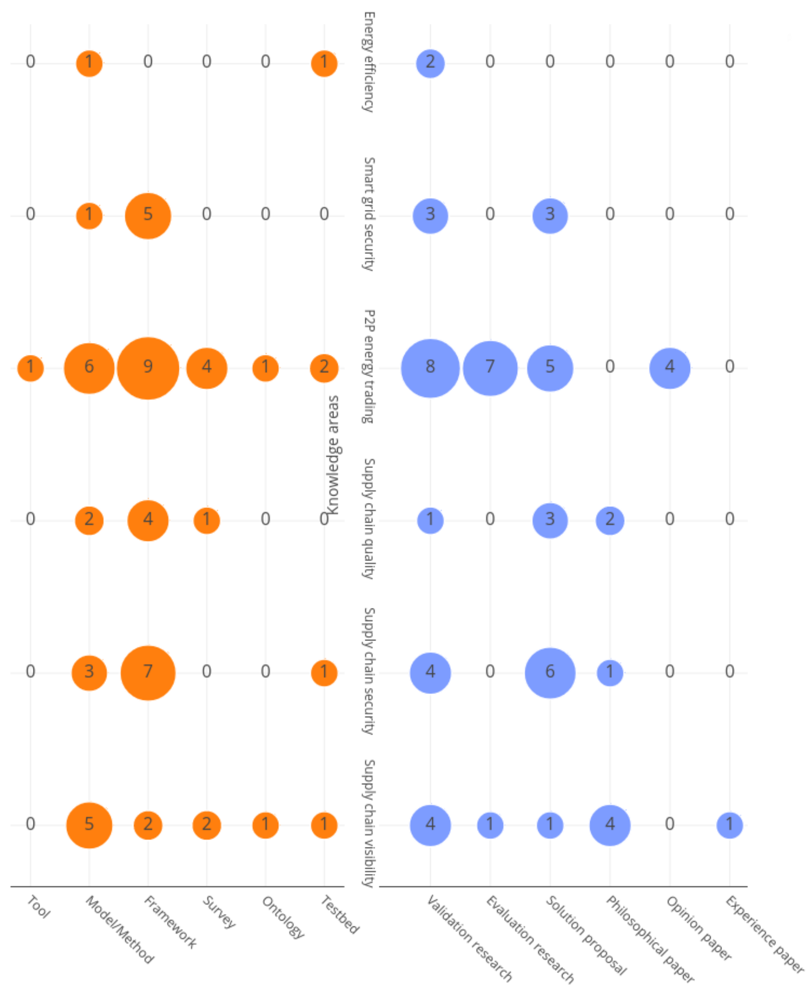

Fig. 4. Publication distribution

As with the papers on energy trading, there are many frameworks and models/methods. Also similarly, it seems that the current issue is to decide on how to go about the real life implementation. Many of the papers look at specific industries or issues. There is as of yet not much focus on agreeing upon a generalized solution. Some companies might want their own specialized supply chain, but as with smart grids, such a system might prove to be problematic when trying to expand.

The papers on supply chains that we found mostly follow the same pattern as the ones on smart grids. However, a key difference is the lack of evaluation research, as witnessed in Figure 4. Evaluation research has to do with verifying that proposed solutions work. The lack of such research hints that there is still a lot to be done on the use of blockchain technology in supply chains. As explained in the World Atlas of Illicit Flows, environmental crime is carried through in part through ”green-washing” products [18]. That is, illegal resources are harvested and then mixed with legit products. If there is no way to tell a legitimate product from a fake, then it is also impossible to know its origin. Proof of origin or Guarantee of origin has been an emphasis on certain supply chain implementations [6][4][5]. Technologies for proof of origin have a wide variety of use cases, several of them possibly benefiting the environment. It should be clear that the possibilities for using blockchain for supply chain management are there. Many researchers have looked at the issue, from various angles. Hence, the question is not whether it is possible, but rather if it is worth it. Jabbar and Bjrn highlight problems with integrating such a system in an already existing supply chain, but end on an optimistic note [14]. The questions are what, then, and what the economic advantages are? As of now, to the best of the authors’ knowledge, no supply chains using blockchain have actually been put into use. Any data on possible savings or profitability in general will, therefore, be based on experiments and simulations. The literature seems to be cautiously positive with regards to the potential of blockchain-based supply chains, so it would in fact seem possible to address sustainability issues using blockchain technology. However, it might prove difficult to convince companies to actually put existing proposals into use [9].

V. Discussion

A. *Smart grids*

Smart and micro grids are becoming popular for a variety of use cases. Examples range from setting up off-grid solutions for rural areas to prosumers selling excess, green energy to their neighbors to replace main-grid energy coming from fossil sources. Two common problems that need to be dealt with are how to incentivize prosumers to produce an excess to sell to others, and how to guarantee the legitimacy of said transaction.

NRGcoin is a proposal by Mihaylov et al., where they set up a virtual market for energy trading in smart grids, with its own cryptocurrency [2]. The currency is generated by supplying energy to the network. Users can also buy energy from others, using the same currency. It would also be possible to exchange the currency for fiat currencies, so one would not be required to sell energy in order to obtain it. Hence, the idea is for participants to balance production and consumption out of self-interest. Mihaylov et al. identified two key issues with the methods found in the literature [2]. As trading is usually done a day in advance, it requires the user 1) predicting the supply and demand ahead of time, and as a result that the user has 2) good knowledge of finance and economy, in order to maximize profits. Their proposal to amend these involves automating a lot of the activity to have it occur with a much higher frequency. They operate with sub-stations for streets, with each one updating every 15 minutes. The prosumers can also inject energy directly into the grid at any time; they do not have to use batteries for storage or hope for net consumption to be at a high at the time. By making buying and selling easier, it becomes possible to adjust prices on the fly, reacting to the market as it changes with highs and lows in consumption. Thus, predicting the expenditure of tomorrow is removed and predicting prices long ahead of time is not needed. Buyers and sellers can place bids with various settings, such as whether to wait if there is no immediately available match, or whether they are willing to accept a different price than they have stated.

B. *Supply chain*

When discussing the use of blockchain technology in supply chains, researchers have covered fields such as pharmaceuticals and farming, using a variety of different implementations [8] [7]. The goal is to improve the quality of the received product and to counteract malicious actors who might want to replace a genuine article with a fake one. Another benefit, as well as important feature, is supply chain visibility for all parties involved.

An important part of blockchain driven supply chains is that they have to be easy to use. If not, the user experience will be negative, leading to an unwillingness to adopt the system. The usability issue comes in addition to the general unwillingness often found in people to adopt new technologies. How to mitigate this unwillingness was studied by Jabbar and Bjrn [14]. They looked at how to introduce blockchain technology to the shipping domain. They describe the domain as being resistant to new technologies, as the existing infrastructure has been built up over a long time. They bring up two very interesting points. First is the term ”infrastructural grind”, with which they refer to what occurs when two information infrastructures are converging. They claim the two will rub off on each other, effectively changing each little by little until they fit. The second is the claim that it is necessary to understand the socio-technical infrastructure. In other words, it is not enough to simply offer an industry what you believe is a better solution, you also have to understand how it would fit in with the potential users.

While there has been substantial research looking into how to apply blockchain technology in order to improve conditions for companies, not much has been done in the way of providing information to consumers. Bettn-Daz et al. propose a methodology for developing supply chain traceability systems, while also keeping the end customer in mind [10]. Even so, it is only briefly mentioned, and the paper features little in the ways of how to actually present the information to a customer.

An issue with developing such systems to collect and display data is that current proposals of supply chains are quite proprietary. That is to say, if companies were to adopt the solutions from current literature, they would likely each have their own systems. Similarly, they would also have to develop their own systems for displaying the information. The wide variety we are seeing is a recognizable pattern of innovation; new technology is introduced, followed by a multitude of attempts at utilizing it. This leads to wildly varying solutions, followed by a slow merging, as certain standards are recognized as superior in some way.

Not many researchers have looked directly at the challenge of environmental crimes, but we believe it is possible to use current proposals found in the literature for this purpose. Supply chain solutions are often aimed towards specific industries, but the underlying methods are more generic. We believe it could be possible to apply existing supply chain management methods in the field of environmental crime. Research points to providing visibility to every party involved and avoiding counterfeit products. These relate directly to the issues of malicious actors mixing illicitly procured goods with genuine products. An issue that has been highlighted as particularly challenging is bridging the gap between the virtual blockchain and the physical products [15][9]. While much research has gone into the virtual part, the part regarding how to register and track a physical product has been largely forgotten, which might be due to the difficulty of solving the problem. There are several papers trying to ensure the validity of a container or similar, for example by using RFID tags or lacquer stamps [3][13]. However, while such solutions might offer a unique identifier that is challenging to copy, they do nothing to keep a malicious actor from tampering with the contents of the container.

In the end, there are definitely promising use cases for blockchain technology in supply chain management. However, the lack of standardization makes it both risky and costly to make the change from conventional solutions. Additionally, there is as of now simply no good way to solve the issue of physical tampering with products.

C. *Software engineering aspects*

We followed the systematic mapping study approach for software engineering described by Petersen et al. [1]. However, we did not find studies focused on the software engineering aspects of developing a blockchain-based system in smart grid and supply chain domain. There are several possible software engineering challenges related to creating and implementing blockchain-based systems, for example:

- How to involve users in defining and eliciting software requirements?
- How to create a flexible architecture that is easy to change and evolve?
- How to verify the functional and non-functional aspects of blockchain-based systems?
- What should the empirical evaluation methods and criteria be for blockchain-based systems?

Figure 1, 2, and 3 show that most studies on the blockchain-based systems for sustainable development are in the early stages. Thus, introducing systematic and rigorous software engineering practices to developing such systems is still a gap to be filled in.

VI. Conclusion and future work

We conducted a systematic mapping study, looking at the relationship between sustainability, as defined through the UN goals, and blockchain technology. More specifically, we focused on the use cases supply chains and smart grids. By doing this, we get an overview of what has been published, and what the researchers have tried to achieve.

We found several studies in the field of smart grids. The different papers often emphasize different aspects, some, for example, looking at how to incentivize prosumers, i.e. participating parties who produce goods rather than consuming them, while others are more focused on how to make the systems resilient towards attacks and exploits. We have also discovered that there does not exist any kind of standardized methodology or framework for developing supply chain management systems. There are, however, several individual implementations to draw inspiration from and to see what they have in common. The experience of existing implementations will be used when looking into how to gather information from the supply chains. For both the main topics in this study, namely smart grids and supply chains, the literature appears to be cautiously optimistic but doubts any huge changes to industry practice. There is potential to improve the industries, but more definite advantages must be discovered and proven in order to incentivize companies to put the technologies into use.

Utilizing software engineering practices in blockchain-based systems meant for improving sustainability is highly relevant. However, our mapping study did not find studies dedicated to software engineering issues, such as development process, requirement engineering, and quality assurance, for developing blockchain-based systems for smart grid or supply chain. As most solution proposals are published in the last two years, few experience paper or evaluation studies, especially studies using empirical software engineering approaches, have been published. Our future work is to study how software engineering theories and practices can help facilitate development and quality assurance of blockchain-based systems for sustainability development.

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