Journal of
Risk and Financial Management

MDPI

Article

Blockchain in the Smart City and Its Financial Sustainability from a Stakeholder's Perspective

Hossein Hassani [1,*], Kujtim Avdiu [2], Stephan Unger [3] and Maedeh Taj Mazinani [4]

[1] Research Institute of Energy Management and Planning, University of Tehran, Tehran 1417466191, Iran
[2] Department of Statistics, Nationalbank Austria, Otto-Wagner-Platz 3, 1090 Vienna, Austria; kujtim.avdiu@oenb.at
[3] Department of Economics and Business, Saint Anselm College, 100 Saint Anselm Drive, Manchester, NH 03102, USA; sunger@anselm.edu
[4] Department of Management, University of Tehran, Tehran 1417466191, Iran; maedetaj@ut.ac.ir
* Correspondence: hassani.stat@gmail.com

Abstract: In this paper, we take a city's budget, which represents the resources that need to be allocated, and test how many blockchain users need to join a voting process of how the city's resources should be allocated in order to best represent their preferences. This voting process can be tracked very well through the utilization of IoT and smart technology in a smart city. Therefore, we showed that the budget resource allocation of a smart city can be significantly optimized through the utilization of blockchain technology. We found that just a tiny fraction of 0.12% of the population of blockchain participants is needed to significantly represent the spending behavior of the total population. This has significant implications as it shows the strength and importance of a required blockchain in a smart city and its minimal energy consumption requirements.

Keywords: blockchain; smart city; IoT; information entropy; sustainability

check for updates

Citation: Hassani, Hossein, Kujtim Avdiu, Stephan Unger, and Maedeh Taj Mazinani. 2023. Blockchain in the Smart City and Its Financial Sustainability from a Stakeholder's Perspective. *Journal of Risk and Financial Management* 16: 393. https://doi.org/10.3390/jrfm16090393

Academic Editors: Thanasis Stengos and David Roubaud

Received: 25 May 2023
Revised: 29 August 2023
Accepted: 30 August 2023
Published: 2 September 2023

1. Introduction

Different institutions such as the UN anticipate that the urban population will reach sixty percent of the world's population by 2050. The growth of cities and urban life will have various, inevitable consequences. Appropriate infrastructures should be provided to fulfill the expected quality of life. The smart city concept was first introduced in 1990. A smart city is a modern urban area that implements massive data to manage resources, systems, and assets efficiently. The data can be gathered through citizens, devices, etc. It can be said that a smart city is a place where traditional services of existing networks in the city become more efficient by using digital solutions, and urban problems will be reduced (Nam and Pardo 2011). The smart city is a multifaceted phenomenon whose dimensions include the intelligence of various sectors such as the economy, transportation, environment, people, life, and governance. Smart cities are based on information and communication technology and use these data for progress and development. There is an extensive network in a smart city that assists municipalities and individuals in making instant decisions on various occasions. Ultimately, the goal of a smart city is to increase the quality of life and speed of various services (Bhushan et al. 2021).

One effective way to facilitate the realization of a smart city is to use blockchain technology (see Treiblmaier et al. 2020). The primary use of blockchain is to buy and sell digital currencies, especially bitcoin. This technology develops day by day and penetrates different sectors in countries. This issue has caused this technology to become a fundamental part of business and markets (Khanna et al. 2021). Blockchain is, in its simplest definition, a system for recording data, but in a new way. In this method, all data are available to all network members. This does not mean insecurity; on the contrary, shared data make the blockchain network completely anti-hackable and impenetrable.

A blockchain is a decentralized network that allows the recording of information that cannot then be permuted, hacked, or manipulated. The key lies in the distributed ledger on which this information is being recorded and then verified by third parties. Each transaction is recorded on the ledger and securely linked together in a so-called block via cryptographic hashes. In our application, we simulate the recording of consumption transactions in a smart city, where nobody sees what the other person consumes, and the city administration can only see the aggregated consumption. The advantage of this technology is its real-time monitoring capability of the prices and type of consumption good or service which is stored in a blockchain. Investors in smart cities can thus see the demand for each good or service. This allows the allocation of investments more efficiently and satisfies the demands of the population.

The advanced level of security allows the establishbment of faster inter-communication of devices due to the decreased necessity of external network security systems that monitor the inputs and outputs of the data access and flow. This is being accomplished by the deployment and integration of the Internet of Things (IoT) into the smart city environment. The infrastructure that enables this faster communication ought to be established via the 5G network, respectively, via the upcoming upgrade to 6G by 2030. The implications of enabling a higher level of communication span from a higher level of productivity within the framework of a smart city to a higher level of security.

The possible application of devices ranges over a variety of fields. Treiblmaier et al. (2020) recognized nine areas of applicability of blockchain technology in the urban smartization: (1) healthcare, (2) logistics and supply chains, (3) mobility, (4) energy, (5) administration and services, (6) e-voting, (7) factory, (8) home, and (9) education. Besides their comprehensive literature review, they also highlighted the significant contribution of IoT in the framework of a smart city. While Treiblmaier et al. (2020) conducted an extensive literature review on the application of blockchain in these categories, we tried to synthesize the general aspect of blockchain applications in smart cities, but from the view point of different stakeholders. These stakeholders are service users and service providers. Our focus lies especially on the financial perspective which enables the financing and investment of smart cities. The crucial aspect we draw attention to is the sustainability aspect with regards to self-sustainability when it comes to the maintenance of a blockchain-based technology system running a smart city and the necessary energy consumption associated with it. All urban difficulties such as traffic congestion, air pollution, crime, and insufficient infrastructure can be tackled using blockchain technology (see Qian 2021; Karger et al. 2021). Moreover, blockchain technology enables the integration of smart devices into everyday life and, thus, increases life quality. From smart banking to healthcare, transportation, energy consumption, and education, blockchain technology has the potential to optimize processes such as transactions and services by minimizing time requirements and errors while increasing simultaneously reliability and predictability (see Hassani et al. 2018; Peters and Panayi 2016; Agbo et al. 2019; Hölbl et al. 2018).

IoT and artificial intelligence offer the possibility to monitor, track, and learn from real-time situations and thus, reduce these typical urban problems. In our case, the implementation of smart contracts allows us to automatize transactions, and thus, to make commercial conduct easier, faster, and more reliable.

Living in a smart city in highly technologized surroundings leads to the formation of a new societal structure. The World Economic Forum (2022) discussed how to combine value to industry with value to society since the *"impact of digitalization on employment is likely to be significant, but the implications of digital transformation extend far beyond the labor market"*. As with any new technology or inception of new societal concepts, there exist drawbacks or potential risks in the implementation of such a new framework to the whole society. One can be attributed to the speed of implementation, which does not allow us to analyze and reflect on the impact of such a rapid deployment on society, as people are highly open to engaging in the integration of their lives in such a new environment. Other factors also exist, such as the danger of constant surveillance, lack of privacy, censorship by a central entity, and prediction and manipulation of not only consumption patterns (Morgan-Thomas et al. 2020) but behavioral patterns in general. Trittin-Ulbrich et al. (2021) explored the dark and unforeseen sides of digitalization.

That is where the implementation and application of blockchain technology become ambiguous. One the one hand, the blockchain itself represents a technology that enables the highest level of privacy and digital security standards available when it comes to peer-to-peer transactions. On the other hand, it enables governments and corporations a level of supervision never before seen in human history if deployed through a centralized layer. According to Sai et al. (2019), decentralization in a public blockchain is characterized as guaranteeing a non-deterministic and probabilistic nature offered as a result of a successful combination of cryptography, distributed systems, and incentive engineering. However, new avenues of centralization are appearing (Gervais et al. 2013). Sai et al. (2021) provided a systematic literature review of the taxonomy of centralization in public blockchain systems.

Our research contributes to the existing literature in two ways. First, we are the first, to the best of our knowledge, to link the potential of blockchain technology to the budget optimization problem of smart cities by simulating the spending behavior of their inhabitants and determining the minimal number of people necessary to map the average spending preferences of a smart city. Second, we address the financial perspective of smart cities concerning potential investment opportunities and returns that can be achieved from the development of smart cities.

Therefore, our research questions addressed the following issues. First, given a certain smart city population size with random spending behavior, where each transaction is tracked on a blockchain, we investigated the minimum number of people necessary to replicate the average spending behavior of an urban city. The second research question we addressed was regarding the investment potential associated with the mapping and tracking of spending behavior, which translates into the classical investment cost vs. return analysis. The investment possibilities range from classical property development investments to the issuance of smart city coins.

This paper contributes to ongoing research in smart cities in terms of its integration of blockchain technology into urban development. While consumption behavior is a very well-studied subject, it remains unclear how spending behavior is influenced by the digitalization of money, especially in light of the tokenization of services offered by the IoT. Therefore, it is crucial to understand how the integration of blockchain technology impacts commercial conduct in the setting of a smart city. Therefore, we intended to understand and determine the number of participating blockchain users necessary to replicate typical urban consumption behavior. For this purpose, we conducted a simulation of a growing blockchain that replicated the number of participants necessary to conduct business. We assumed random consumption behavior with log-normal deviations from typical consumption behavior, which we obtained through the CPI basket of New York City. By letting the number of blockchain participants grow, it is possible to measure the significance threshold at which the employment of a blockchain replicates the typical spending behavior of an urban population.

In addition, we focused on the valuation of stakeholder interests associated with a smart city framework, including the associated financing and energy consumption problem of running a blockchain in a smart city. This implies the consideration of the costs for the provision and consumption of services, i.e., energy costs.

Another issue we considered in this paper is the problem regarding the required energy consumption by blockchain users. Therefore, we investigated, through simulation, how many blockchain participants are required to statistically significantly replicate the consumption preferences with respect to the spending behavior of the population of an entire smart city. For this purpose, we utilized consolidated U.S. CPI weight components and compared them with the prospective budget allocation of New York City. We ran a simulation and counted the number of joining blockchain participants who can, by performance of a smart contract, automatically vote on how the budget should be allocated until the real spending distribution according to the CPI weights reached with 95% confidence.

A smart city is a sustainable and efficient city with a high quality of life intending to meet urban challenges. The most important challenges are the improvement of mobility, social development, health, and security, optimizing resource usage, supporting economic growth, and participatory governance. Solving challenges is achieved by using information and communication technologies in services and infrastructure, cooperation between stakeholders (citizens, universities, government, and industry), and social capital investment (Mosannenzadeh and Vettorato 2014).

The smart city concept has been developed in three main areas: 1. academia, 2. industry, and 3. government. Academic literature has a holistic and comprehensive approach. Business literature focuses on commercial and industrial tools, in which the concept of "smart" implies intelligent services and products, artificial intelligence, and thinking devices (Nam and Pardo 2011).

Furthermore, the governmental interpretation of "smart" should be viewed mainly from the urban development perspective originating from the urban planning theory of "smart growth" of the 1990s. Regardless of its diverse interpretations, the use of technology and social innovation seems to be the central issue in this concept.

A smart city comprises connected devices that transfer data using wireless and cloud technology. The ultimate goal of a smart city is to provide a higher quality of community life and increase government efficiency. The measurement criteria of a smart city are its ability to provide for citizens' social and economic needs in addition to improving their quality of life (Khanna et al. 2021). Necessary infrastructures, mainly smart homes and buildings, which are possible through IoT technology, should be provided (Bhushan et al. 2020). The IoT-capable devices mentioned in these articles are a requirement for the realization of the real-time voting process we employed in this research.

A glimpse at existing smart city projects in the world reveals a variety of goals, distinctions, and similarities, such as the reduction of carbon footprints, achieving energy efficiency, achieving the highest quality living environment possible for residents, developing green areas within the city, developing advanced and widely available information infrastructure, achieving both economic growth and a high standard of life, growing sustainable communities, and ensuring social compatibility between various groups of residents (Ojo et al. 2015). These are just some of the factors real-time voting processes can achieve as they reveal and channel structural consumption preferences and the demand of a given population.

Kitchin (2013) listed a number of examples and detailed how cities are being instrumented with digital devices and infrastructure that produce "big data", enabling real-time analysis of city life, new modes of urban governance, and providing the raw material for envisioning and enacting more efficient, sustainable, competitive, productive, open and transparent cities. He also reflected on five concerns regarding smart cities: the politics of big urban data, technocratic governance, and city development, the corporatization of city governance, technological lock-ins, buggy, brittle, and hackable cities, and the panoptic city concept. Our research shows that one of the widespread fears of total surveillance, potentially caused by the transparent real-time tracking of consumption, can be ruled out if policies and the supply of goods and services are only directed after significance sampling of the population. It is sufficient to track the consumption behavior of only a tiny fraction of the population to satisfy the demands and needs of the average population.

Moreover, blockchain technology also has potential to bridge the security gap that exists in the healthcare industry when it comes to patient health information and data security. The integration of blockchain technology in smart city concepts enables healthcare providers to address these security challenges (Qiu et al. 2018).

The Internet of Things (IoT) plays an important role in the practical implementation and application of blockchain technology in smart cities. Blockchains offer the necessary protocols and ledgers upon which transactions and communications, e.g., via smart contracts, can take place. Potential smart applications range from intelligent transportation to industry 4.0 and smart banking, among others, for boosting the quality of life of citizens. Ibba et al. (2017) highlighted the importance of sensors to produce digital measurements, which are useful for investigating and studying the quality of life in every part of the city. Smart contracts utilize sensor information and implement a control logic, which enables the blockchain to respond to the demand of availability and unchangeability. This technology appears to be of immense importance if real-time voting processes ought to be tracked to track consumption behavior.

However, Majeed et al. (2021) stressed that blockchain and smart cities are in their infancy and significant research efforts are needed to properly integrate them.

Further, Bhushan et al. (2020) provided a review of blockchain technology and its role in dynamically optimizing city resources which, in turn, has the potential to boost the daily life of citizens in terms of healthcare, transportation, energy consumption, and education. Moreover, blockchain technology provides a variety of good features, such as trust-free, transparency, pseudonymity, democracy, automation, decentralization, and security, which are helpful in improving smart city services and promoting the development of smart cities (Xie et al. 2019). As we stress later in this article, the potential of blockchain integration in a smart city environment bears significant investment potential through excess returns, which can be achieved through properly meeting the demands of the population.

Mora et al. (2017) provided a bibliometric analysis of the literature published between 1992 and 2012. They stressed that due to the fast-growing topic of smart cities, much of the generated knowledge about them concerns only technological development. They also find two paths of literature, namely, one of European universities and one of the U.S. business community. Due to this fragmentation, the future development of research associated with smart cities might be undermined. However, we showed, through the results of our research, that even two different paths can share common ground when it comes to the development of smart cities, which is the sustainable financing of these projects.

Mora et al. (2018) conducted a case study on best practices for European smart city development. They also listed various dichotomies that generate a critical knowledge gap in smart city development. Addressing this issue, Mora et al. (2020) proposed a theory that addresses the existing different smart-city-related concepts and constructed a model that maps the causal mechanisms associated with sustainable smart city transitions.

Different aspects and examples of blockchain-based applications in smart cities were also given by Trencher and Karvonen (2019), who addressed the health and well-being of human beings in urban development. They conducted a case study about smart health in Kashiwanoha Smart City in Japan and found that the pursuit of greater health and well-being extends smart city activities beyond technological innovation and impacts resident lifestyles, and increasing their social relevance. Thus, if planned properly, smart cities have the potential to tackle social problems and to become sustainable, equitable, and liveable cities. All these outcomes can only be achieved when the financing of smart cities is attractive to investors. This is where our research shows the importance of the integration of blockchain technology in the smart city environment, as it incentivizes investments due to a higher expected rate of return for investors.

Furthermore, very closely related to our paper is the research carried out by Karvonen et al. (2020) and Paskaleva et al. (2017), who examined how data governance in particular is framed in the new smart city agenda that is focused on sustainability. By looking at three use cases and a stakeholder survey, they showed how the governance of data can underpin urban smart and sustainable development solutions. Moreover, Karvonen et al. (2020) explored various ways in which smart cities are influencing and being influenced by urban planning by highlighting the important role of digitalization in urban planning.

Research has not only been in favor of smart cities. Calzada and Cobo (2015) critically analyzed the technological determinism of smart cities by suggesting that being digitally connected should not be perceived as gaining social capital. They explored hyper-connected societies and how unplugging could be beneficial. However, as our results indicate, unplugging hyper-connected societies would lead to sub-optimal information dissipation and thus, eventually, to a decreased standard of living.

With respect to our research, the hyper-connection of a smart city population is a prerequisite to map the spending behavior on a blockchain.

Concerning the potential of blockchain applications in smart cities, existing research suggests that smart monitoring helps to reduce energy consumption.

Chui et al. (2018) addressed the question of energy sustainability in urban area development. They discussed the role of parallel, artificial intelligence and cognitive computing as catalysts in a process aimed at designing and optimizing the supply and utilization of smart services in urban space. In particular, they considered smart metering and non-intrusive load monitoring (NILM) to profile electric appliances' electricity consumption. The role of energy consumption is, in particular, important when it comes to the employment of blockchains. Therefore, the energy consumption issue is an important one which we also address in the next chapter. Our research revealed that only a tiny fraction of a smart city's blockchain infrastructure would be necessary to benefit its inhabitants and its investors. Therefore, the necessary energy consumption problem is, rather, a problem of satisfying the needs of the population.

A very important instrument to control energy consumption caused by transactions of products and services is smart contracts. Krichen et al. (2022) provided an overview of the state-of-the-art formal methods applied on smart contract specification and verification. Their aim was to minimize the risk of faults and bugs and avoid the resulting costs. Brousmiche et al. (2018) presented an agent-based simulation framework to experiment with blockchain-backed energy market places and perform a sensitivity analysis to assess the impact of parameters on economics and blockchain system performances. Brousmiche et al. (2020) looked into the strengths of Ethereum in peer-to-peer energy trading by analyzing a physical demonstrator deployed on Raspberry Pis, autonomous agents simulating the energy consumption and production behavior of four households as well as their buying/selling behavior.

All these factors are important to consider when it comes to the deployment and integration of blockchain technology into a smart city framework. From the examples addressed in existing literature, we can already see that the utilization of blockchain technology could increase quality of life, foster economic growth, and lead to more effective resource usage. An important factor that should be considered in the implementation of smart contracts is the utilization of formal methods. They can be used to verify the correctness of smart contract codes, which can help to prevent costly errors and security breaches. Formal methods include mathematical techniques for modeling, designing, and testing software and hardware systems to ensure they are constructed correctly (Krichen et al. 2022).

Krichen et al. (2022) reviewed formal methods of smart contract specification and verification to minimize the risk of fault and bug occurrence and avoid the resulting costs. Smart contracts play an important role when in the execution of transactions of goods and services. Since they are at the core of any real-time consumption behavior monitoring, their seamless functionality is very important.

Another branch of smart city and blockchain research tackles the issue of e-governance. Khanna et al. (2021) explored the potential of blockchain technology as an enabler for e-governance in smart cities and identify various areas of e-governance wherein blockchain can provide monumental advantages: 1. energy trading, 2. smart healthcare, 3. e-voting, 4. supply chain, and 5. real estate. Citizen participation in the decision-making process will see a significant increase thanks to the involvement of technologies such as blockchain, IoT, and AI (Khanna et al. 2021).

Rathee et al. (2021) considered the design and implementation of and e-voting mechanism through IoT devices using blockchain technology. Concepts such as this are crucial when it comes to the integration of blockchain technology in the smart city environment. Since the real-time monitoring of consumption patterns reflects real-time voting on consumption preferences, the process of tracking these transactions can be seen as a process of democratization. As we show in the upcoming chapter, only a tiny fraction of recorded transactions is necessary to reflect the broad consumption preferences of a population.

In Section 2, we provide an overview of the materials and methods. In Section 3, we present the results of the proposed models. In Section 4, we discuss the implications of representative voting behavior mapping via blockchain and what role it plays when it comes to the sustainable financing of a smart city. We provide conclusions in Section 5.

2. Fields of Applicability of Blockchain Technology

Blockchain emerged in recent years and was first conceived as the bitcoin mechanism. While it is proved that the idea behind blockchain works appropriately, it dominates several areas. It can be said that blockchain will mutate the way any digital data are processed. Data in blockchain are shared in a peer-to-peer network (Khanna et al. 2021). One of the most critical areas is the smart city. Many scholars have explored the use of the blockchain to construct a smart city (Bhushan et al. 2020; Khanna et al. 2021). Blockchain empowers network members to trade information with a deep level of unwavering quality and straightforwardness without requiring an incorporated administrator. Urban communities have an assortment of partners, and trading information among partners is fundamental for profoundly advantageous metropolitan administrations. One crucial attribute of this technology is to save time and decrease effort. Nowadays, several cities worldwide are using blockchain technology, and smart cities are growing with its help (Khanna et al. 2021). In the following, blockchain applications and implications in smart cities are discussed from various aspects.

2.1. Financial Applications

Blockchain can lead to very high financial transparency and a high-speed system in a smart city, which is very important in financial projects. This system in smart cities makes all the expenses and money spent and the taxes received by the cities completely transparent. It also makes transfers of currencies quicker and less expensive than the existing services, which is beneficial for business owners. This capability affects both people and the government because it minimizes the possibility of embezzlement, money laundering, or receiving unusual expenses. People can pay all their employees' salaries and benefits at a low cost without heavy taxes. The crowdfunding model can change with blockchain because it makes the funding process available from anywhere in the world. This model is anonymous, more prosperous, and free of borders, and startups can monitor the whole process. Lenders and insurance providers can benefit from blockchain by providing smart contracts. Lenders can use blockchain to perform collateralized loans through smart contracts, which are based on transaction codes between parties rather than paper contracts.

Smart contracts built on the blockchain allow certain events to automatically precipitate service payments, margin calls, full loan repayment, and the release of collateral. Anyone in the blockchain can execute smart contracts, resulting in quicker loan processing, better rates, cheaper costs, and the lack of involvement of individuals in checking accounts and financial payments. Recording all claims on a blockchain would keep customers from making duplicate claims for the same event.

Furthermore, using smart contracts can speed up the process for claimants to receive payments. Since this system is not hackable, no one can transfer money without informing others. Another critical pillar in a financial transaction is intermediaries such as banks. With blockchain, avoiding intermediaries becomes possible. One can make a transaction using virtual wallets. By eliminating intermediaries, blockchain reduces fees, inflation, and costs, increasing service delivery and speeding up financial transfers.

We analyze the financial aspect of blockchain in smart cities, i.e., through cryptocurrencies and tokenization, in Section 4.

2.2. Urban Management

Cities are growing, and infrastructures, as mentioned before, should grow simultaneously and scale quickly, for instance, smart streets or traffic lights. Smart traffic lights gather new data to control the traffic in crowded intersections. It also strengthens the culture of using public transport. This goal is achieved by giving priority to the movement of public transport. In other words, in traffic, public vehicles have more time to pass, and therefore people who travel by bus instead of private cars reach their destinations faster.

Blockchain can increase the ability to track information and increase security in the supply chain by increasing, collecting, transferring, and sharing valid data at all stages of production, processing, warehousing, distribution, and sale. Reliance on Radio Frequency Identification (RFID), a wireless system that uses electromagnetic fields to automatically identify and track tags attached to objects, and the Internet of Things, along with blockchain-based reliability enhancement, can increase the trustworthiness of the knowledge gained from the repository and improve its usability (Tian 2016). The two most important features of the blockchain are its distribution and sequencing. In this context, the parties agree on the details of the chain (Yli-Huumo et al. 2016). One of the most significant achievements of using blockchain is ensuring that the data are not manipulated and the accuracy of the information, which, at the macro level, ensures the availability of reliable knowledge. According to the literature, there are three main flows of material, money, and information in the supply chain, which are completely interdependent (Eaidgah et al. 2016). The chain is produced with the flow of money and materials in the continuous information supply. Researchers are dedicating significant efforts to improve the flow of information. Due to the breadth and variety of issues in the supply chain, on the one hand, and the modernization of blockchain technology, on the other hand, there are still significant challenges in this area, including traceability and trustworthiness.

2.3. Governmental Benefits

Electronic governance focuses on improving government capabilities, simplifying processes, reducing costs, and saving time (Oliveira et al. 2020).

The adoption of blockchain technology can upgrade the level of governmental services. Identity management and elections are among the most affected ones. Digital identity storage using blockchain can be implemented in several fields such as voting, welfare programs, healthcare, and social security. Elections face several challenges, including manipulation and errors in many developing countries, which result in less credibility. E-voting systems are introduced to alleviate the challenges mentioned above (Daramola and Thebus 2020). Conventional systems are exposed to cyberattacks due to centralized systems, which blockchain technology solves (Ayo et al. 2011). Utilizing blockchain via voting through smartphones prevents users from voting twice and the possibility of altering the votes.

In addition, the expenses of holding elections can be reduced. Several scholars have proposed blockchain e-voting systems. Countries that apply these systems include Estonia, India, Turkey, and South Korea (Bulut et al. 2019). There are rare works that consider this issue in the case of national election requirements. As a result, decision-makers do not have an explicit vision of the potential risks or consequences of applying blockchain on a national scale (Daramola and Thebus 2020). Authors have discussed how the Architecture Trade-off Analysis Method could help stakeholders understand the potential risks. South Africa was chosen as a case study to propose a blockchain architecture (Daramola and Thebus 2020). In the case of welfare or charity programs, fraud and operations costs could be decreased. In the meantime, service users can receive funds more quickly through digital disbursement on the blockchain. Blockchain can change the working context of doctors and other medical professionals. Patient information in the existing, traditional system may be scattered between different departments, which can affect the accessibility of data at the appropriate time (Wang et al. 2020). An efficient sharing system in the healthcare system can lead to better diagnosis and expense optimization (Gai et al. 2019). Maintaining medical records helps medical professionals access precise patient information, thereby making timely treatment possible. In addition, it can be merged with the insurance system to see whether the treatment cost is covered or not. In this regard, several researchers have focused on applying blockchain in various aspects of the healthcare field, including secure health data storage (Wang et al. 2020; Al Omar et al. 2017; Azaria et al. 2016; Xu et al. 2019; Yue et al. 2016). Agbo et al. provided a systematic review of blockchain technology in healthcare, which paves the way for other researchers to accelerate blockchain applications in the healthcare field (Agbo et al. 2019).

Applying blockchain technology in the agricultural sector has many benefits for farmers and consumers. Blockchain can be combined with the Internet of Things and artificial intelligence, enabling manufacturers to achieve high productivity in all seed stages and consumers to trace their produce from farm to the table. Some artificial intelligence programs consider soil and crop monitoring systems. These systems allow farmers to identify specific crop disease patterns and perform therapeutic measures. Providing agricultural product information ensures customer satisfaction and loyalty. Data storage and distribution are also crucial in the food supply chain and contribute to today's agricultural products' commercial success. Many startups worldwide are using blockchain in agriculture. The main activity of these startups is divided into five main groups: tracing the production route of consumed agricultural products, product and supply chain management, smart contracts and sales, insurance services, and farm equipment management (Lin et al. 2018; Mirabelli and Solina 2020; Ølnes et al. 2017).

2.4. Technological Applications

Data security is one issues that can be improved significantly through blockchain. It enhances cloud data security by storing it across the node network instead of centralized storage units. As a result, the data do not depend on a central entity, and any data attack will not be pernicious. In this regard, special events such as natural disasters and rebellions will not be a threat anymore.

The Internet of Things makes conventional devices smart and autonomous. The IoT is vulnerable to security challenges because of devices connected to public communication technologies such as WiFi (Ali et al. 2020). Securing Internet of Things networks is of great importance due to its dominance in urban life and smart cities. Several researchers discuss the blockchain's capability to bolster the IoT's trustworthiness (Minoli and Occhiogrosso 2018; Ali et al. 2018). Storing IoT data on a decentralized network instead of a centralized server strengthens the security and invariableness of blockchain, making tampering almost impossible.

2.5. Smart City Budget Optimization through Blockchain-Based Spending Behavior Mapping

Next, consider a practical use case under the implementation of a blockchain in a smart city and its potential impact on spending behavior. Our key hypothesis is that through utilization of the blockchain technology, budget resource allocations of a smart city can be optimized. For this purpose, we present the use case, the simulated model, and the results in this chapter.

3. Data and Methodology

Allocative efficiency can be achieved through maximization of information entropy (Unger 2019). Considering budgetary resources, the key characteristic of de-centralization of allocative choice is that information entropy is maximized, where the probability distribution that best represents the current state of knowledge exhibits the greatest entropy of the system. As the number of nodes in a network increases, entropy also increases. In our case, a de-centralized ledger serves as the perfect example of potential allocative efficiency as the number of blockchain users increases. A city's budget represents the resources that need to be allocated. Therefore, we want to test how many blockchain users need to join a voting process of how the city's resources should be allocated in order to best represent their preferences.

We assumed, in our model, a smart city with a population of 1 million people and whose spending behavior is not known a priori. However, we assumed to know the a posteriori distribution of spending preferences of these people by assuming that their spending behavior on average can be replicated through the weight distribution of the consumer price index (CPI). Therefore, we took the 2019–2020 US CPI weights for urban consumers (CPI-U), which measures the consumer price index for all urban consumers, from the U.S. Bureau of Labor and Statistics (U.S. Bureau of Labor and Statistics 2019–2020) and worked with the weight distribution of the consumer price index (CPI).

In order to contrast the divergence from a real city's budget allocation, we compared the consolidated CPI component weight distribution with the consolidated budget allocation weight distribution of New York City's 2021–2025 budget (New York City Independent Budget Office 2021–2025).

Table 1 reports the U.S. CPI-U weight distribution from 2019–2020 and the NYC budget allocation weight distribution for 2021–2025. One can see the discrepancy between the proposed spending and the actual, realized spending, which represents the needed, or wished for, allocation by the population. The question we are interested in is the following: if the allocation process could be replicated though a voting process, processed through a smart contract on a blockchain, such as Ethereum, how many users would it need to achieve a spending distribution which significantly represents the whole population?

Table 1. U.S. CPI-U weights (2019–2020) vs. NYC budget allocation weights 2021–2025.

CPI		NYC_2021–2025	
Housing, Food and Apparel	59.08%	Housing and Economic Development, Public safety, and Food and Apparel	25%
Transportation	18.18%	Transportation	15%
Medical care	8.49%	Health and Social Services, Sanitation	9%
Recreation	5.11%	Parks, Libraries, and Cultural Sites	8%
Education	6.41%	Education	20%
Other goods and services	2.74%	General Services, Environmental Protection	23%

The voting process starts with the first blockchain user. We replicated a blockchain user's vote by simulating their spending preference weights, following a log-normal distribution around each of the CPI component weights from the distribution with mean = CPI weights and sigma = 25%. To estimate the preferred spending distribution, we independently simulated the weights of each CPI component by using a log-normal distribution.

Next, by performing a Chi-square test, we evaluated the deviation of the simulated spending distribution to the actual spending distribution, where the actual spending distribution is measured through the CPI-U weight distribution. In each iteration, one blockchain user is added with a randomly sampled spending distribution and log-normally distributed around the actual spending distribution. The threshold for terminating the iterations is reached when the p-value for each of the component weights exceeds the 5% level.

Our null hypothesis, H_0, states that the spending distribution of randomly sampled blockchain users does not correspond to the spending distribution of the total population. In other words, we tested how many blockchain users we need to be able to make a significant statement about the mean of the spending distribution of the population. The threshold at which the p-value exceeds the 5% level reveals, at the same time, the number of blockchain users needed to replicate real spending distribution as the null hypothesis can be rejected at this level. The Chi-Square homogenous test, χ^2, tests if the difference between the expected spending distribution and the observed spending distribution is significant. We accept our null hypothesis as long as

$$1 - p_{value} = P\left[\chi^2 > \chi^2_{0.05}\middle|H_0\right] > 0.05. \quad (1)$$

In order to test our assumption, we conducted the Chi-Square test over different iterations, where each iteration adds a new blockchain user with random weights of his spending distribution. To perform the Chi-Square test for simulated spending distribution, we classified, for each component, the actual, resp. expected spending distribution weight:

- w_i^a: Actual spending distribution weight;
- w_i^e: Expected spending distribution weight, and conducted the test.

$$\chi^2 = \frac{(w_i^a - w_i^e)^2}{w_i^e} \quad (2)$$

4. Results

We next provide the results from our performed simulations as well as the corresponding sampling distributions for each aggregated CPI component, compared to the expected CPI weight distribution.

Table 2 reports the simulation results of calculating the number of required blockchain participants in order to achieve a significant result, using 1 million iterations with increments of 100 participants. We can see that the required number of participants was fairly small. Notably, the average number of required blockchain users was 1183, which represents 0.12% of the total assumed population of the smart city in our use case. The results indicated that just a tiny fraction of the inhabitants of the smart city would need to participate in order to create a representative, statistically significant spending distribution. The learned insights could be utilized by either the policy and decision of the smart city in order to optimize the budget allocations according to the people's wants, or they could be directly implemented through smart contracts in such a way that, e.g., property taxes and other utilities and fees are directly routed and allocated according to the voted spending preferences. Since a small sample would already replicate a statistically significant proportion of the preferred spending distribution of the whole population, the budget resources would be optimally allocated and frictions, costs, and spending of non-productive money minimized.

Table 2. Simulation results of calculating required blockchain participants to achieve a significant result, using 1 million iterations with increments of 100 participants.

CPI	Blockchain Participants	Expected Mean	Sampling Mean	*p*-Value
Housing, Food & Apparel	1100	59.08%	59.67%	0
Transportation	1200	18.18%	18.36%	0.00004
Medical care	1000	8.49%	8.40%	0.00012
Recreation	1400	5.11%	5.36%	0.00352
Education	1300	6.41%	6.34%	0
Other goods and services	1100	2.74%	2.71%	0.0012

The results appear to be reasonable since the spending behavior across a population did not deviate too much from the average. Thus, a small sample of blockchain users already suffices to ensure that budget resources are optimally distributed according to the wishes and needs of the population.

The simulation we conducted started with the simulation of the consumption habits of all inhabitants of the city according to the known CPI weights. We assumed that not all people participate in the blockchain. Therefore, we wanted to test how many people have to participate in the blockchain so that the sample of their spending behavior becomes significant with the mean of the New York City CPI weights. Our assumed number of inhabitants was 1 million. With increasing increments of 100 people, we let more and more people participate in the blockchain and ran, after each iteration, a statistical test to check if the resulting consumption distribution replicated the actual spending distribution. This became the case as soon as the 95% significance level of the Chi-Square test was reached. Figure 1 reports the comparison between the sampling distribution and the expected distribution of the consolidated CPI weight components. The expected CPI distribution was generated by the simulation of a population of size 1 million with normally distributed CPI weights. These CPI weights reflect the average spending behavior and deviation across this population. The sampling distribution displayed the generated distribution after reaching the corresponding number of blockchain participants as reported in Table 2 for each consolidated CPI component. We can see the shape of the sampling distributions at a 95% confidence level. The results showed the high accuracy of just a tiny fraction of blockchain participants, which suffices to replicate the average spending preferences of a population. We took the CPI weights as target weights since they serve as a realistic benchmark for evaluating consumer behavior in an urban environment. We can rule out any sampling bias as each iteration and CPI weight uses the same log-normal distribution with the same CPI weight mean and constant standard deviation of assumed 25% for each CPI weight for every new participant. This ensures that each new participant has the same pre-conditions when he is added to the blockchain and does not learn from the consumption behavior of the previously added blockchain participants. Certain constraints of the model might be prevalent due to the chosen distribution.

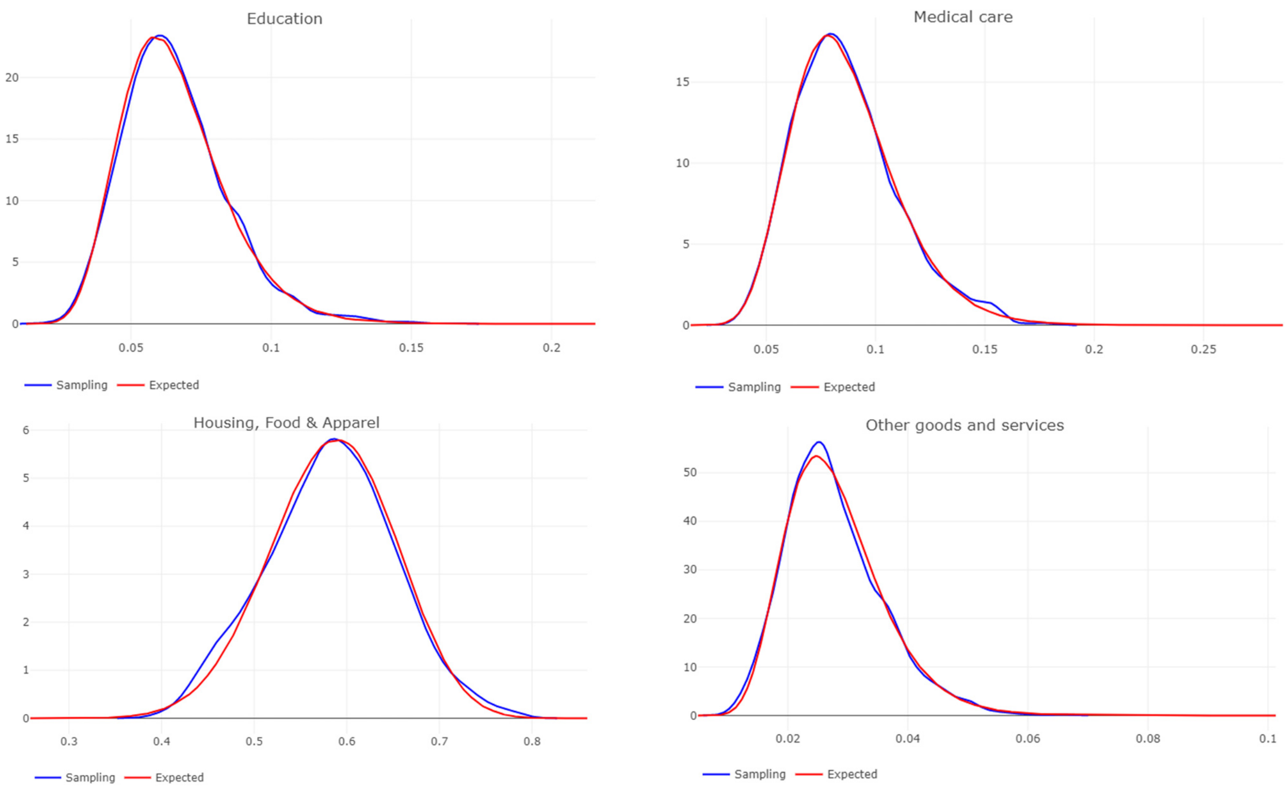

Figure 1. *Cont.*

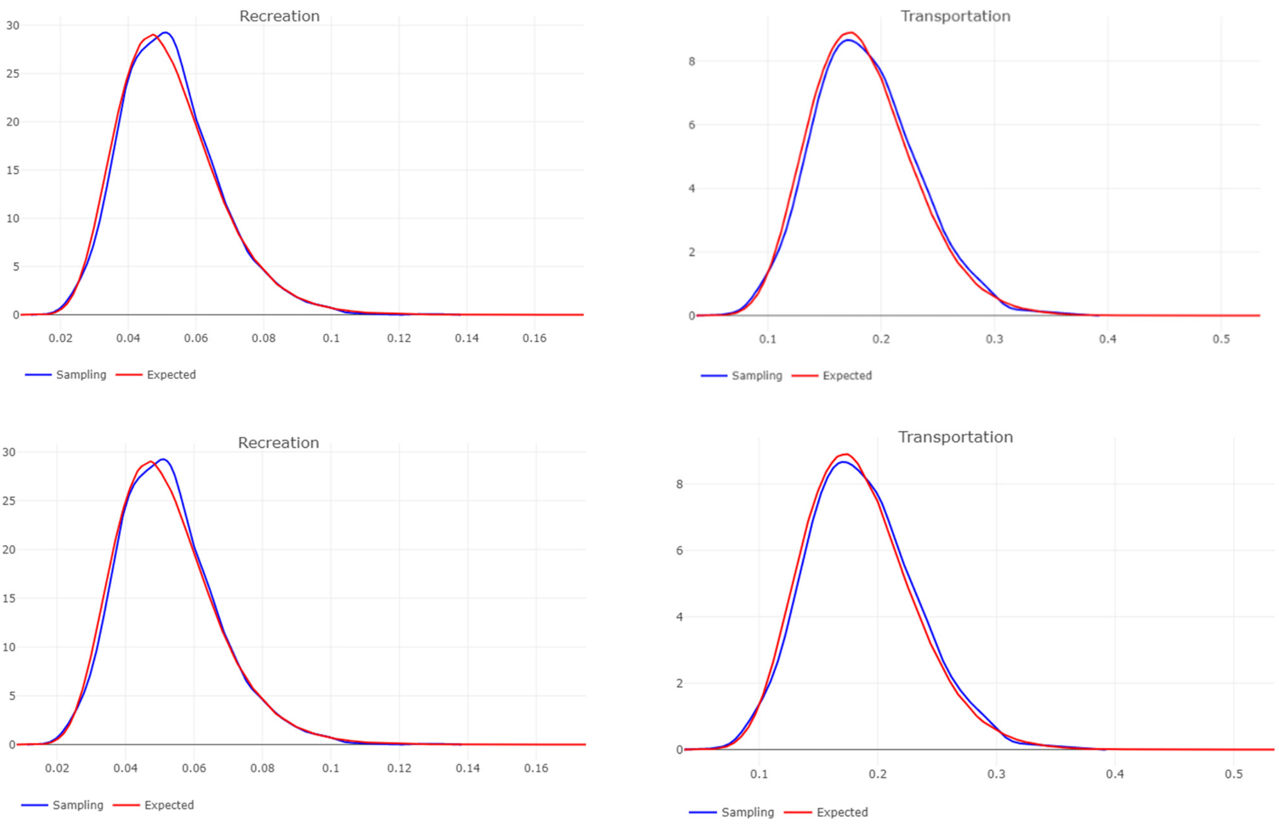

Figure 1. Cumulative density functions of sampling distribution vs. expected distribution of consolidated CPI weight components.

Robustness

In order to test if our simulation results are robust, we ran several simulations with different assumed standard deviations, ranging from 0% to 50%. The standard deviation reflects a potential change in consumer respective to spending behavior. We can see from Figure 2 that the amount of blockchain participants necessary to replicate the real spending behavior did not significantly change. This is an indication that the number of people necessary to replicate the CPI weights was around a very low level of around 0.12%.

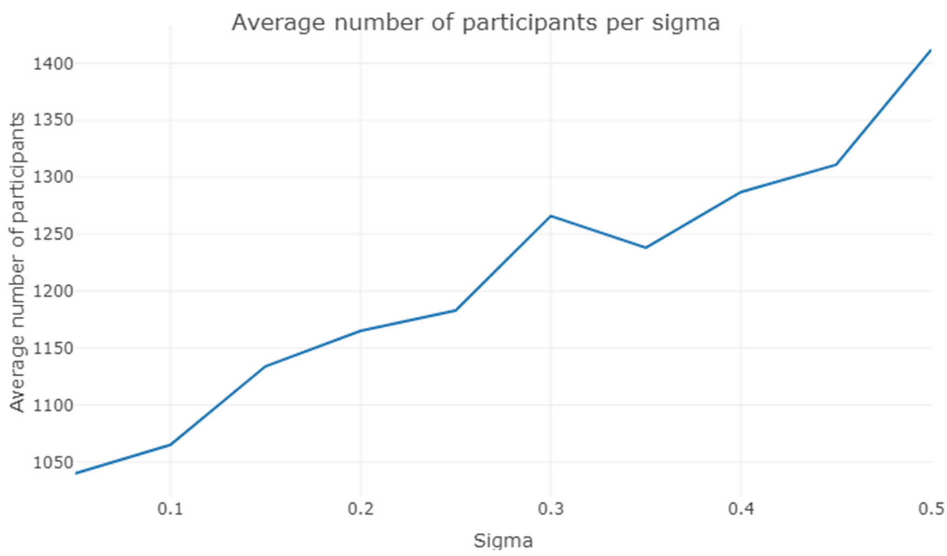

Figure 2. Robustness check: blockchain participant simulations with different spending behaviors, from sigma = 0% to 50%.

5. Discussion

Our results revealed a lot about potential solutions to our two main research questions. The first one about the minimum number of people necessary to replicate the average spending behavior of an urban city was answered by our simulation results, and the second one about the investment potential in smart cities associated with this mapping and tracking of spending behavior arose out of the insights gained from the first research question. We next discuss the implications of the results on our two research questions.

5.1. Representative Voting Behavior Mapping via Blockchain

Being able to track and monitor spending behavior allows us to better reflect the wishes and preferences of the population. Real-time tracking of demanded goods and services enables corporations, city councils, and governments to better adjust their offerings in these goods and services to meet a population's demands.

The question is if it is necessary to track everyone and everywhere. The answer to this question is no. Our simulation showed that tracking a tiny fraction of the population of just 0.12% allowed the actual spending preferences to be mapped in such a way that a city's expenditures and budgetary accounting average satisfied the majority of the population's spending preferences.

One of the main reasons that only such a tiny fraction is necessary to map a whole population's spending preferences is, probably, that the typical spending behavior can be averaged out across the whole population. This means that the changes in preferences from one person to the next person are not too significantly high when it comes to the satisfaction of basic needs, which are accounted for in a city's budget. The main expenses that are accounted for are mainly general categories such as education, medical care, housing, food and apparel, recreation, transportation, and other goods and services.

These categories do not go down to a granular level, where preferences will probably differ much more than on an aggregate level. Nevertheless, using blockchain technology, it would be possible to even go down to this granular level in order to map the individual's granular preferences. The question that would arise out of this potential is the utility. Since the differences in individual preferences will vary a lot, utilization of these insights would be a hard task, and might not even pay off.

The tracking of real-time spending preferences reflects a real-time voting process on available or not-available goods and services. This real-time voting process can be performed very efficiently using smart technology such as IoT, smart meters, tokens, etc. The blockchains can serve as the ledger where all entries of these votes are registered and monitored. Therefore, the implementation of such technology in a smart city concept allows for performing these real-time voting processes.

The implications of the implementation and utilization of such technology are manifold. Besides the democratization of consumption preferences by transparent real-time consumption behavior, the implications for investments in such cities, and therefore, the increase in quality of life and standard of living, are significant. Like any investment, the most basic benchmark to perform is a classical investment cost vs. return analysis. The revenues generated by investments in such technology and infrastructure must outweigh the costs; otherwise, no sustainable operation is possible. The revenues can be achieved through various channels, realized through the devices and the infrastructure outlaid above, and encompass property development investments to the issuance of smart city tokens. We next discuss the potential of smart city investments.

5.2. Smart City Investments

One of the most important implications of the invention of blockchain technology, besides its ability to increase privacy, security, and efficiency, is its power to accelerate urban development. This can mainly be attributed to the flexibility that comes along with potential applications of blockchain, from real-time communication between devices, to improve energy efficiency, to conducting financial transactions. Blockchain always serves as a fundamental technology that allows the performance of these applications. Since smart cities utilize this blockchain technology, the efficiency, and thus the financial attractiveness, of investing in the development of smart cities is increasing. In this section, we take a closer look at the financing aspect of smart cities, i.e., the channels that exist to fund smart cities, as well as the financial sustainability of smart cities, with regard to the marginal cost of maintaining a smart city vs. the marginal benefit for society.

An important aspect that should be stressed is the potential risks and dangers associated with the incorporation of blockchain technology in urban development. These can be legislative uncertainty, technological barriers, and cybersecurity concerns. The first point concerns the legislative uncertainty around the lawful implementation and utilization of utility tokens. While under current legislation, the issuance, use, and trade of utility tokens is permitted without any regulation, security tokens require the same legal know-your–customer requirements such as any type of financial asset. However, given the rapid development in legislation, it cannot be ruled out that certain applications of utility tokens might be restricted as well, which leads to investment uncertainty.

Second, technological barriers caused by energy shortages and increasing energy costs might lead to discouragement in investment. Further, the current level of artificial intelligence is still at a crossroads, where complete autonomous administration still needs human supervision and is not capable of administering ledgers containing real-time consumption.

Third, with increasing dependency on the functioning of the economy and commercial conduct on digital frameworks, the exposure to cyber security risk increases exponentially since the incentive for cyber security attacks grows proportionally to the risk exposure. The increased incentive to find vulnerability in social-technological systems leads to an increased need for monitoring, tracking, and supervision, which in turn raises, again, concerns about privacy and democratic problems.

Urban development is one of the most capital-intensive undertakings of society. Therefore, different types of lenders are required when it comes to financing the planning and construction of new urban areas. The focus lies in the long-term monetization of real estate projects, the technological development of infrastructure through the establishment, settlement, and expansion of private businesses, office places, housing space, and public facilities. The idea behind smart cities is the integration of modern technology under the requirement of efficiency. Efficient operability of processes in a smart city prevents unnecessary marginal costs in operations, such as those caused by energy profligacy, and, thus, ensures a higher long-term return on investment. This auspicious outlook on higher and more stable returns triggers a re-enforcing effect by attracting more long-term capital, and thus, in turn, promotes sustainability. Nevertheless, the investment in smart cities remains very capital-intensive besides its building costs, especially when it comes to its maintenance. While the stakeholders expect a higher long-term marginal benefit in its establishment through the realization of social and economic benefits, the costs for building and operating a smart city remain substantial. As (Deloitte 2022) mentions, "as cities look to upgrade their infrastructure with smart technologies, paying for those projects presents a significant challenge of introducing smart technologies on a wide-scale basis. Constrained by tight budgets, cities need to identify business models that can help to attract private financing in order to make the introduction viable and financeable." They identify the following different types of financing models: 1. financing model payments (payments received that match agreed cost (including finance) amounts, allowing full coverage of expenditure and agreed returns); 2. availability payments (payments received that are linked with the performance of the private sector operator and availability of the service/asset in line with agreed performance standards); 3. savings sharing (certain services will generate savings for the public sector. If quantifiable and accountable, those savings can generate a budget to help fund the associated assets/service); 4. shadow tolls (the public sector makes payments to the private sector based on usage of the service/asset. In some cases, recurring payments may apply so as to reduce risk); 5. user fees/charges (users pay directly for services (e.g., road tolls). This tends to be riskier than public sector payments as it is more difficult to quantify in advance with any certainty); 6. rate-type payments (the public sector collects revenues from the public and utilizes these to pay the private sector for specific services/assets (e.g., power generation/water utilities); 7. pay-as-you-go (the user is charged for each use of the service. Can be collected using the billing system of the mobile operator); 8. subscription (the user pays a fixed amount for service regardless of level of usage); and 9. advertising-based (revenue streams are generated by selling advertising on asset space, rather than collecting from individual users. This allows service providers to provide service free (or inexpensively) to users. An example is Wi-Fi kiosks in New York that provide a free service underwritten by advertising income).

Along with typical funding strategies, such as project financing, traditional loans and leases, vendor financing, consumption-based financing, "as-a-service" financing, concession financing, revenue share financing, and equity financing, there are two approaches to smart city funding which are widely used, i.e., value capture and asset recycling. While in direct value capture the value is directly generated within a project, using strategies such as revenue sharing, profit sharing, refinancing gain share, user fees, and impact fees, indirect value capture creates value as a result of government decisions (e.g., a zoning change) or investments (e.g., developing a new transit system) that benefit developers (Deloitte 2022).

In asset recycling, the government sells (or leases) a public asset to a private entity for value and then uses the proceeds to fund future investments. The government might sell an asset it no longer needs; sell an asset to take advantage of its current capital value and then lease it back for public use; or conduct an asset swap or share arrangement to help with a private sector development plan. In each case, the goal is to use existing assets to enhance the overall government portfolio while achieving value for money (Deloitte 2022).

The European Investment Bank, as the financial branch of the European Union, finances a lot of smart city projects. They utilize the following investment products for financing smart cities: 1. investment loans, which usually amount to at least EUR 25 m; 2. framework loans, which are used to finance multiple small and medium-sized projects ranging from 1 to 50 m during a medium-term of 3–5 years; 3. equity investment, i.e., through pure private equity funds or financial instruments that consolidate grant and commercial funding; 4. intermediated loans through local banks or other intermediaries to establish customized smart city programs, which consequently on-lend to final beneficiaries such as SMEs and local authorities; and 5. investment platforms such as the European Fund for Strategic Investments (EFSI), a pool of other public and private financing for investment in a portfolio of projects with a given thematic and/or geographic focus (European Investment Bank 2022).

An increasing stream of financing activity emerges through public–private partnerships. The characterization of public–private partnerships is that cities are partnering with private organizations to advance smart city projects. Since stakeholders are increasingly taken into account in urban development, the synergies of public and private know-how and financial capabilities can be utilized. This emergence is mainly driven by tighter budgets and the need for technological innovation. Liu et al. (2021) analyzed existing research published on public–private partnerships (PPPs) for the development of smart city projects and aimed to identify the emerging themes and recommend mechanisms and strategies for improved use of smart city PPPs. They identified five themes in PPP application for smart city development: (1) technological innovation integration and increased risk profile; (2) smart citizen engagement and participatory governance; (3) data sharing and information security; (4) transformation of the PPP process and approach; and (5) PPPs for urban sustainability. Mirzaee and Sardroud (2022) also named nonprivate sector partnerships (Non-PSPs), debt markets, and PPPs as feasible alternatives to funding and financing in such cities. Milenkovic et al. (2017) proposed a case for public–private partnership models for smart city financing in Croatia. The advantages of PPP models include the increased utilization of financial leverage and potential access to governmental-linked institutions that can provide resources. Additionally, it is more likely that more stakeholders will be included in PPP models. Nevertheless, PPP models have also drawbacks since the involvement of governmental structures means bureaucratic procedures, which make decision processes longer and more complex. Moreover, the PPP partnerships bear a risk of unilateral lobbying and influence on innovation development on the private sector side.

One of the strongest potentials of blockchain is its applicability to real-time transactions utilized through cryptocurrencies. More and more companies issue their own tokens and accept payments in cryptocurrencies. Thinking of the integration in a smart city, this concept opens unlimited possibilities to transform the way we transact and conduct business. Electric mobility providers for the public or private sector will be able to debit and credit customers in real time through 5G and 6G networks. 6G networks are expected to be deployed around 2030. They are an upgrade of 5G networks and will be able to use higher frequencies than 5G networks, which translates into the provision of higher transmission capacities and reduction of latency to a level where microsecond communication will be possible. These communication networks are part of the critical infrastructure of a city. The IoT ensures real-time communication and necessary transactions between devices and objects, utilized through cryptocurrencies. The underlying communication standard can be smart contracts such as Ethereum. The Ethereum platform is a decentralized, open-source blockchain with smart contract functionality and can be used to build a blockchain network to buy, sell, or rent a property (Dewan and Singh 2020). The coins exchanged in the Ethereum network are ethers rather than bitcoins (Wood 2015). The problem smart cities face is linked to their own sustainability. Due to its requirement of constant digital exchange and transaction verification, the blockchain requires an enormous amount of energy to sustain its operability. Fadeyi et al. (2020) contextualized energy use in smart cities through the mining of virtual currencies in order to predict whether or not smart cities can truly be sustainable if crypto-mining is sustained (Fadeyi et al. 2020). The question of the future sustainability of smart cities is whether the energy consumption required for the operation of the underlying blockchain can served through renewable energy or not. The problem smart cities face is that with ongoing time and expansion of the blockchain, the mining and verification process becomes more and more energy-intensive, mainly because of the cooling necessity of the mining machines. This implies that the core requirement for sustainability is that the rate at which renewable energy is being produced must be equal to or bigger than the energy consumed by the smart technology itself. Ethereum's digital currency is known to require approximately half of total Bitcoin energy consumption. Hashrate is taken into account during the power use calculations by machines (Fadeyi et al. 2020). Bitcoin, for instance, uses around 2.6 gigawatts and has been estimated to reach about 8 gigawatts eventually (Fadeyi et al. 2020). To get a feeling for the scale, China's mining venture in Monero may have added about 5% of global electricity consumption (to mine the same coin), which was at 646 GWh as of 2018 (Li et al. 2019), implying that roughly 20,000 tons of carbon may have been discharged into the environment between a space of eight months of the year under review (Wood 2015). Mining operations will yield hash calculations to attain a marginal cost (MC) that is at par with the marginal product (MP). Figures by (Mora et al. 2017) in mid-March, 2018 revealed that MP reached approximately EUR 13.7 million. In order to examine and forecast electricity costs resulting from mining from the economic perspective, vital factors such as the production cost for an average mining machine, average life span, and average unit cost of electricity should be taken into consideration (Fadeyi et al. 2020). As electricity cost per lifetime of an average machine can be pegged at 60%, and depending on the electricity costs of the source which provides the corresponding smart city with electricity, for a smart city to operate sustainably, the marginal product always needs to exceed the marginal cost.

6. Conclusions

Blockchain technology is a relatively recent invention of our century, which attracts businesses striving for improvement and increased security of their operations. With the growing volume of digital data circulating in our daily lives, there is a clear need for the data security, access, transparency, and integrity that blockchain can provide. We analyzed the application of blockchain technology to smart cities from four different perspectives: people as service users, government as service providers, and technology aspects, as well as the financial aspect. We found an enormous amount of possible application fields of blockchain within the framework of smart cities, including healthcare services, administration services, communication, banking services, production, processing, warehousing, distribution, sales, building security, cyber security, energy optimization, emission reduction, etc. The framework in which these applications take place is the Internet of Things (IoT). Smart devices are connected with each other and able to communicate, allowing a real-time transfer of data and thus a real-time processing of tasks and operational necessities. By utilization of 5G and upcoming 6G network technology, functional operability is ensured such that latency is minimized. The implications are far-reaching since the speed at which real-time communication can take place leads to enormous efficiency gains through the optimization of processes. The basis for the functionality of such networks in smart cities is blockchain technology, which enables the utilization of such processes through smart contracts and protocols such as Ethereum. The possibilities arising from this technology are endless.

In this paper, we considered the interoperability of IoT devices as enabling the tracking of consumption behavior. A smart city serves as a perfect experimental playground since the integration of IoT devices is widely spread in such urban developments. Assuming that all transactions are saved on a ledger of a blockchain, it is possible to retrieve product and consumption preferences. We simulated the generation of such a blockchain in order to find out how many inhabitants' random spending behavior must be tracked in order to replicate an average urban spending behavior. The insights gained from this simulation have important implications for the development and investment into smart cities since they shows which type of blockchain would be suitable for such a task and which products and services are most likely to be consumed given the track record of a certain number of people. We found that the spending behavior tracking of a tiny fraction of just 0.12% of the population suffices to significantly replicate the spending pattern of the population of an entire smart city. This shows the power and importance of blockchain, as just a small fraction of a population would be needed to join a smart city blockchain in order to fairly represent their spending and voting behavior.

However, certain drawbacks arise with the complete transformation of cities to smart cities and their dependency on decentralized networks. One of these problems is the question of the energy efficiency of a blockchain when it comes to its self-sustainability in terms of the required energy for the cooling and mining process.

Moreover, certain limitations of this study must be considered. First, we assumed log-normal spending behavior of randomly added blockchain participants. Future research may consider different spending distributions with insights borrowed from consumption psychology. Secondly, the direct relationship between spending behavior tracking, blockchain implementation, and potential returns of investments into smart cities needs to be explored more in-depth. We suggest analyzing use cases where the real implementation of blockchains for transactional spending has already taken place and estimating the investment necessary to develop such infrastructure.

We provide important insights for smart city developers, investors, and administrators. The implications for the stakeholders are manifold, as the potential investment in infrastructure and supply chains depends on the form of blockchain and voting system deployed, as well as the ability of the administration to track and monitor consumer behavior in real-time.

Author Contributions: Conceptualization, H.H., K.A., S.U. and M.T.M.; methodology, H.H., K.A., S.U. and M.T.M.; writing—review and editing, H.H., K.A., S.U. and M.T.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data is available upon request.

Conflicts of Interest: The authors declare no conflict of interest.

References

Agbo, Cornelius C., Qusay H. Mahmoud, and J. Mikael Eklund. 2019. Blockchain technology in healthcare: A systematic review. *Healthcare* 7: 56. [CrossRef] [PubMed]

Al Omar, Abdullah, Mohammad Shahriar Rahman, Anirban Basu, and Shinsaku Kiyomoto. 2017. Medibchain: A blockchain based privacy preserving platform for healthcare data. Paper presented at the International Conference on Security, Privacy and Anonymity in Computation, Communication and Storage, Guangzhou, China, December 12–15.

Ali, Muhammad Salek, Massimo Vecchio, Miguel Pincheira, Koustabh Dolui, Fabio Antonelli, and Mubashir Husain Rehmani. 2018. Applications of blockchains in the Internet of Things: A comprehensive survey. *IEEE Communications Surveys & Tutorials* 21: 1676–717.

Ali, Rashid, Yazdan Ahmad Qadri, Yousaf Bin Zikria, Fadi Al-Turjman, Byung-Seo Kim, and Sung Won Kim. 2020. A blockchain model for trustworthiness in the internet of things (IoT)-based smart-cities. In *Trends in Cloud-Based IoT*. Cham: Springer, pp. 1–19.

Ayo, Charles K., J. O. Daramola, and A. A. Azeta. 2011. Developing a Secure Integrated E-Voting System. In *Handbook of Research on E-Services in the Public Sector: E-Government Strategies and Advancements*. Hershey: IGI Global, pp. 278–87.

Azaria, Asaph, Ariel Ekblaw, Thiago Vieira, and Andrew Lippman. 2016. Medrec: Using blockchain for medical data access and permission management. Paper presented at the 2016 2nd International Conference on Open and Big Data (OBD), Vienna, Austria, August 22–24.

Bhushan, Bharat, Aditya Khamparia, K. Martin Sagayam, Sudhir Kumar Sharma, Mohd Abdul Ahad, and Narayan C. Debnath. 2020. Blockchain for smart cities: A review of architectures, integration trends and future research directions. *Sustainable Cities and Society* 61: 102360. [CrossRef]

Bhushan, Bharat, Preeti Sinha, K. Martin Sagayam, and J. Andrew. 2021. Untangling blockchain technology: A survey on state of the art, security threats, privacy services, applications and future research directions. *Computers & Electrical Engineering* 90: 106897.

Brousmiche, Kei-Léo, Andra Anoaica, Omar Dib, Tesnim Abdellatif, and Gilles Deleuze. 2018. Blockchain energy market place evaluation: An agent-based approach. Paper presented at 2018 IEEE 9th Annual Information Technology, Electronics and Mobile Communication Conference, Vancouver, BC, Canada, November 1–3.

Brousmiche, Kei-Léo, Pascal Menegazzi, Olivier Boudeville, and Eric Fantino. 2020. Peer-to-peer energy market place powered by blockchain and vehicle-to-grid technology. Paper presented at 2020 2nd Conference on Blockchain Research & Applications for Innovative Networks and Services (BRAINS), Paris, France, September 28–30.

Bulut, Rumeysa, Alperen Kantarcı, Safa Keskin, and Şerif Bahtiyar. 2019. Blockchain-based electronic voting system for elections in turkey. Paper presented at the 2019 4th International Conference on Computer Science and Engineering (UBMK), Samsun, Turkey, September 11–15.

Calzada, Igor, and Cristobal Cobo. 2015. Unplugging: Deconstructing the Smart City. *Journal of Urban Technology* 22: 23–43. [CrossRef]

Chui, Kwok, Miltiadis Lytras, and Anna Visvizi. 2018. Energy Sustainability in Smart Cities: Artificial Intelligence, Smart Monitoring, and Optimization of Energy Consumption. *Energies* 11: 2869. [CrossRef]

Daramola, Olawande, and Darren Thebus. 2020. Architecture-centric evaluation of blockchain-based smart contract e-voting for national elections. *Informatics* 7: 16. [CrossRef]

Deloitte. 2022. The Challenge of Paying for Smart Cities Projects. Available online: https://www.deloitte.com/au/en/Industries/infrastructure/perspectives/challenge-paying-smart-cities-projects.html (accessed on 15 August 2023).

Dewan, Surbhi, and Latika Singh. 2020. Use of blockchain in designing smart city. *Smart and Sustainable Built Environment* 9: 695–709. [CrossRef]

Eaidgah, Youness, Alireza Arab Maki, Kylie Kurczewski, and Amir Abdekhodaee. 2016. Visual management, performance management and continuous improvement: A lean manufacturing approach. *International Journal of Lean Six Sigma* 7: 187–210. [CrossRef]

European Investment Bank. 2022. Available online: https://www.consilium.europa.eu/en/policies/investment-plan/strategic-investments-fund/ (accessed on 15 August 2023).

Fadeyi, Oluwaseun, Ondrej Krejcar, Petra Maresova, Kamil Kuca, Peter Brida, and Ali Selamat. 2020. Opinions on Sustainability of Smart Cities in the Context of Energy Challenges Posed by Cryptocurrency Mining. *Sustainability* 12: 169. [CrossRef]

Gai, Keke, Zhihui Lu, Meikang Qiu, and Liehuang Zhu. 2019. Toward smart treatment management for personalized healthcare. *IEEE Network* 33: 30–36. [CrossRef]

Gervais, Arthur, Ghassan Karame, Srdjan Capkun, and Vedran Capkun. 2013. Is Bitcoin a Decentralized Currency? *Cryptology ePrint Archive*. Available online: https://eprint.iacr.org/2013/829 (accessed on 15 August 2023).

Hassani, Hossein, Xu Huang, and Emmanuel Silva. 2018. Banking with blockchain-ed big data. *Journal of Management Analytics* 5: 256–75. [CrossRef]

Hölbl, Marko, Marko Kompara, Aida Kamišalić, and Lili Nemec Zlatolas. 2018. A Systematic Review of the Use of Blockchain in Healthcare. *Symmetry* 10: 470. [CrossRef]

Ibba, Simona, Andrea Pinna, Matteo Seu, and Pani Filippo Eros. 2017. CitySense: Blockchain-oriented smart cities. Paper presented at the XP2017 Scientific Workshops (XP '17), Cologne, Germany, May 22–26. Article 12. New York: Association for Computing Machinery.

Karger, Erik, Marvin Jagals, and Frederik Ahlemann. 2021. Blockchain for Smart Mobility—Literature Review and Future Research Agenda. *Sustainability* 13: 13268. [CrossRef]

Karvonen, Andrew, Matthew Cook, and Håvard Haarstad. 2020. Urban Planning and the Smart City: Projects, Practices and Politics. *Urban Planning* 5: 65. [CrossRef]

Khanna, Abhirup, Anushree Sah, Vadim Bolshev, Michal Jasinski, Alexander Vinogradov, Zbigniew Leonowicz, and Marek Jasiński. 2021. Blockchain: Future of e-Governance in Smart Cities. *Sustainability* 13: 11840. [CrossRef]

Kitchin, Rob. 2013. The real-time city? Big data and smart urbanism. *GeoJournal* 79: 1–14. [CrossRef]

Krichen, Moez, Mariam Lahami, and Qasem Abu Al-Haija. 2022. Formal methods for the verification of smart contracts: A review. Paper presented at 2022 the 15th International Conference on Security of Information and Networks (SIN), Sousse, Tunisia, November 11–13.

Li, Jingming, Nianping Li, Jinqing Peng, Haijiao Cui, and Zhibin Wu. 2019. Energy consumption of cryptocurrency mining: A study of electricity consumption in mining cryptocurrencies. *Energy* 168: 160–68. [CrossRef]

Lin, Jun, Zhiqi Shen, Anting Zhang, and Yueting Chai. 2018. Blockchain and IoT based food traceability for smart agriculture. Paper presented at the 3rd International Conference on Crowd Science and Engineering, Singapore, July 28–31.

Liu, Tingting, Sherif Mostafa, Sherif Mohamed, and Tuan Son Nguyen. 2021. Emerging themes of public-private partnership application in developing smart city projects: A conceptual framework. *Built Environment Project and Asset Management* 11: 138–56. [CrossRef]

Majeed, Umer, Latif U. Khan, Ibrar Yaqoob, S. M. Ahsan Kazmi, Khaled Salah, and Choong Seon Hong. 2021. Blockchain for IoT-based smart cities: Recent advances, requirements, and future challenges. *Journal of Network and Computer Applications* 181: 103007, ISSN 1084-8045. [CrossRef]

Milenkovic, Melita, Mario Rašić, and Goran Vojkovic. 2017. Using public private partnership models in smart cities—proposal for croatia. Paper presented at the 2017 40th International Convention on Information and Communication Technology, Electronics and Microelectronics (MIPRO), Opatija, Croatia, May 22–26.

Minoli, Daniel, and Benedict Occhiogrosso. 2018. Blockchain mechanisms for IoT security. *Internet of Things* 1: 1–13. [CrossRef]

Mirabelli, Giovanni, and Vittorio Solina. 2020. Blockchain and agricultural supply chains traceability: Research trends and future challenges. *Procedia Manufacturing* 42: 414–21. [CrossRef]

Mirzaee, Ali, and Javad Majrouhi Sardroud. 2022. Public–private-partnerships (PPP) enabled smart city funding and financing. In *Smart Cities Policies and Financing*. Amsterdam: Elsevier, pp. 117–31.

Mora, Luca, Mark Deakin, and Alasdair Reid. 2018. Strategic Principles for Smart City Development: A Multiple Case Study Analysis of European Best Practices. *Technological Forecasting and Social Change* 142: 70–97. [CrossRef]

Mora, Luca, Mark Deakin, Xiaoling Zhang, Michael Batty, W. Martin Jong, Paolo Santi, and Francesco Appio. 2020. Assembling Sustainable Smart City Transitions: An Interdisciplinary Theoretical Perspective. *Journal of Urban Technology* 28: 1–27. [CrossRef]

Mora, Luca, Roberto Bolici, and Mark Deakin. 2017. The First Two Decades of Smart-City Research: A Bibliometric Analysis. *Journal of Urban Technology* 24: 3–27. [CrossRef]

Morgan-Thomas, Anna, Laurence Dessart, and Cleopatra Veloutsou. 2020. Digital ecosystem and consumer engagement: A socio-technical perspective. *Journal of Business Research* 121: 713–23. [CrossRef]

Mosannenzadeh, Farnaz, and Daniele Vettorato. 2014. Defining smart city. A conceptual framework based on keyword analysis. *TeMA-Journal of Land Use, Mobility and Environment*, 683–94. [CrossRef]

Nam, Taewoo, and Theresa A. Pardo. 2011. Smart city as urban innovation: Focusing on management, policy, and context. Paper presented at the 5th International Conference on Theory and Practice of Electronic Governance, Tallinn, Estonia, September 26–29.

New York City Independent Budget Office. 2021–2025. Available online: https://www.ibo.nyc.ny.us/publicationsAnnuals.html (accessed on 15 August 2023).

Ojo, Adegboyega, Edward Curry, Tomasz Janowski, and Zamira Dzhusupova. 2015. Designing next generation smart city initiatives: The SCID framework. In *Transforming City Governments for Successful Smart Cities*. Berlin/Heidelberg: Springer, pp. 43–67.

Oliveira, Thays A, Miquel Oliver, and Helena Ramalhinho. 2020. Challenges for connecting citizens and smart cities: ICT, e-governance and blockchain. *Sustainability* 12: 2926. [CrossRef]

Ølnes, Svein, Jolien Ubacht, and Marijn Janssen. 2017. Blockchain in government: Benefits and implications of distributed ledger technology for information sharing. *Government Information Quarterly* 34: 355–64. [CrossRef]

Paskaleva, Krassimira, James Evans, Christopher Martin, Trond Linjordet, Dujuan Yang, and Andrew Karvonen. 2017. Data Governance in the Sustainable Smart City. *Informatics* 4: 41. [CrossRef]

Peters, Gareth W., and Efstathios Panayi. 2016. *Understanding Modern Banking Ledgers through Blockchain Technologies: Future of Transaction Processing and Smart Contracts on the Internet of Money*. Berlin/Heidelberg: Springer International Publishing, pp. 239–78.

Qian, Zhiqi. 2021. The integration of blockchain and artificial intelligence for a smart city. *Academic Journal of Computing & Information Science* 4: 37–41.

Qiu, Jinglin, Xueping Liang, Sachin Shetty, and Daniel Bowden. 2018. Towards Secure and Smart Healthcare in Smart Cities Using Blockchain. Paper presented at the 2018 IEEE International Smart Cities Conference (ISC2), Kansas City, MO, USA, September 16–19; pp. 1–4. [CrossRef]

Rathee, Geetanjali, Razi Iqbal, Omer Waqar, and Ali Bashir. 2021. On the Design and Implementation of a Blockchain Enabled E-Voting Application Within IoT-Oriented Smart Cities. *IEEE Access* 9: 34165–76. [CrossRef]

Sai, Ashish Rajendra, Jim Buckley, and Andrew Le Gear. 2019. Assessing the security implication of Bitcoin exchange rates. *Computers & Security* 86: 206–22.

Sai, Ashish Rajendra, Jim Buckley, Brian Fitzgerald, and Andrew Le Gear. 2021. Taxonomy of centralization in public blockchain systems: A systematic literature review. *Information Processing & Management* 58: 102584.

Tian, Feng. 2016. An agri-food supply chain traceability system for China based on RFID & blockchain technology. Paper presented at the 2016 13th International Conference on Service Systems and Service Management (ICSSSM), Kunming, China, June 24–26.

Treiblmaier, Horst, Abderahman Rejeb, and Andreas Strebinger. 2020. Blockchain as a driver for smart city development: Application fields and a comprehensive research agenda. *Smart Cities* 3: 853–72. [CrossRef]

Trencher, Gregory, and Andrew Karvonen. 2019. Stretching "smart": Advancing health and well-being through the smart city agenda. *Local Environment* 24: 610–27. [CrossRef]

Trittin-Ulbrich, Hannah, Andreas Georg Scherer, Iain Munro, and Glen Whelan. 2021. Exploring the dark and unexpected sides of digitalization: Toward a critical agenda. *Organization* 28: 8–25. [CrossRef]

Unger, Stephan. 2019. The effect of allocative efficiency of free markets on entropy and its implications on taxes. *Athens Journal of Business & Economics* 5: 287–300. Available online: https://www.athensjournals.gr/business/2019-5-4-2-Unger.pdf (accessed on 15 August 2023).

U.S. Bureau of Labor and Statistics. 2019–2020. Weights, Consumer Price Index (CPI-U). Available online: https://www.bls.gov/opub/mlr/2020/ (accessed on 15 August 2023).

Wang, Ziyu, Nanqing Luo, and Pan Zhou. 2020. GuardHealth: Blockchain empowered secure data management and Graph Convolutional Network enabled anomaly detection in smart healthcare. *Journal of Parallel and Distributed Computing* 142: 1–12. [CrossRef]

Wood, Gavin. 2015. Available online: http://gavwood.com/paper.pdf (accessed on 15 August 2023).

World Economic Forum. 2022. Available online: https://reports.weforum.org/digital-transformation/understanding-the-impact-of-digitalization-on-society/ (accessed on 6 February 2022).

Xie, Junfeng, Helen Tang, Tao Huang, F. Richard Yu, Renchao Xie, Jiang Liu, and Yunjie Liu. 2019. A Survey of Blockchain Technology Applied to Smart Cities: Research Issues and Challenges. *IEEE Communications Surveys & Tutorials* 21: 2794–830. [CrossRef]

Xu, Jie, Kaiping Xue, Shaohua Li, Hangyu Tian, Jianan Hong, Peilin Hong, and Nenghai Yu. 2019. Healthchain: A blockchain-based privacy preserving scheme for large-scale health data. *IEEE Internet of Things Journal* 6: 8770–81. [CrossRef]

Yli-Huumo, Jesse, Deokyoon Ko, Sujin Choi, Sooyong Park, and Kari Smolander. 2016. Where is current research on blockchain technology?—A systematic review. *PLoS ONE* 11: e0163477. [CrossRef] [PubMed]

Yue, Xiao, Huiju Wang, Dawei Jin, Mingqiang Li, and Wei Jiang. 2016. Healthcare data gateways: Found healthcare intelligence on blockchain with novel privacy risk control. *Journal of Medical Systems* 40: 1–8. [CrossRef] [PubMed]