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Research paper

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Abstract

A decade after Satoshi Nakamoto published his famous whitepaper, blockchain technology (BT) has started to become widely recognized and used beyond the cryptocurrency Bitcoin. While the financial sector is the most prominent adopter of the technology, numerous other fields of application for the ground-breaking innovation are discussed by researchers and practitioners alike. One key area in which blockchain-based applications are expected to drive radical and disruptive innovation is smart cities. BT provides unique benefits which smart cities can leverage to improve quality of life, administrative processes, and environmental sustainability. However, due to the entrepreneurial dynamics and abundant fields of application for BT in smart cities, an integrated and boundary-spanning analysis is lacking. Thus, our paper aims at analysing how BT is used in different smart city business models to present a multi-layer taxonomy. For this purpose, we identified a global sample of 80 startups which offer products or services for smart cities and examined their business models. The paper explores economic and technological characteristics of blockchain based smart city applications. These unique insights will be useful for researchers, practitioners, and regulators.

Keywords: blockchain, smart city, taxonomy, business model.

1 Introduction

Blockchain technology (BT) has the potential of changing how our cities work and how we live in them. The blockchain, an innovation with general purpose character, represents a new form of a database technology with the novelty of being fully distributed (Beck, Czepluch, Lollike and Malone, 2016). Prior to BT, an intermediary was needed to control, maintain, and oversee databases and networks. Due to new consensus mechanisms, the blockchain enables every network member to contribute to the network and work as a control instance (Davidson, De Filippi and Potts, 2016). With first use cases in finance and banking, the technology is triggering game-changing applications in further sectors. Because of its decentralized nature and potential for automation, smart cities are an important field of application for the BT. The initiative “Smart Dubai”, for instance, aims at creating urban solutions based on BT by 2020 (Rizzo, 2017).

With the world’s population expected to exceed 9 billion people by the year 2050 and more than half of the population living in cities, urban areas are facing the challenge of managing the rapid growth in a sustainable way. In smart cities, information and communication technologies (ICTs) are used to address the challenges inherent to a growing population in urbanities. These challenges occur in areas such as pollution, resource shortages, governance, or transportation. The main idea behind smart cities is to connect people, institutions and infrastructures to use resources more sustainably and efficiently (Harrison and Donnelly, 2011). Smart cities aim at reshaping all areas of life within cities including traffic handling, water and waste management, energy consumption, or smart living (Chourabi et al., 2012).

Given the high relevance of BT for applications beyond finance such as smart cities (Swan, 2015), the literature on concrete blockchain use cases is surprisingly scarce. Moreover, prior literature has focused primarily on technological features of BT, but neglected the economic implications of using BT. Prior taxonomies have examined BT in the fields of governance and architecture (Glaser, 2017; Xu et al., 2017), fintech (Beinke, Nguyen and Teuteberg, 2018), entrepreneurial finance (Chanson, Risius and Wortmann, 2018; Fridgen, Regner, Schweizer and Urbach, 2018; Kazan, Tan and Lim, 2015), and general applications (Labazova, Dehling and Sunyaev, 2019). The objective of our study is to provide insights on the economic and technological characteristics of blockchain-based smart city applications to develop a taxonomy which enables researchers and practitioners to understand, evaluate, and structure blockchain-based smart city innovations. To achieve this goal, we offer an in-depth analysis of how startup firms build upon BT to increase the efficiency, sustainability, and life quality in urban agglomerations. Therefore, we consider solutions for the smart city core areas including energy, transportation, building, health, and government (Komninos, Pallot and Schaffers, 2013; Washburn et al., 2009). We focus on startup firms since radical and disruptive innovations frequently emerge from these new market entrants rather than incumbents (Chesbrough, 2006; Weiblen and Chesbrough, 2015).

The remainder is structured as follows: First, we elaborate on the study's background. Next, we explain our research design. In the following section, we present the results of our analysis. The paper concludes with a discussion of the results, limitations, and opportunities for further research.

2 Background

2.1 Blockchain technology

When Satoshi Nakamoto published his seminal work in 2008, he intended to create Bitcoin as an electronic peer-to-peer (P2P) cash system (Nakamoto, 2008). However, blockchain as the underlying technology of Bitcoin offers a great potential beyond cryptocurrencies and applications in the financial sector. At its core, BT is a distributed database that is curated by several participants in a P2P network. Changes to the database are initiated using public key cryptography and updated following a consensus mechanism. The history and current structure of the database are rendered immutable by hash functions in a chain of blocks (Beck et al., 2016). BT offers an innovative solution to the Byzantine Generals' Problem as it allows two anonymous parties to securely exchange information over an unreliable network without relying on an intermediary (Zheng, Xie, Dai and Wang, 2016).

Since a decade, Bitcoin has successfully proved the feasibility of blockchain-based transfer of value. Yet, BT also facilitates other types and more complex transactions. The broader applicability is mainly based on two extensions of Nakamoto's original idea. First, BT can be used to store so-called smart contracts as source code which are automatically executed without human interference once prespecified events occur. Similar to the exchange of Bitcoins, which also follows a simple and highly standardized set of rules, sophisticated smart contracts have the potential to automate many types of transactional contracts such as spot market purchases or machine-to-machine transactions (Sikorski, Haughton and Kraft, 2017). To facilitate token issuance and smart contracts, Blockchain protocols such as Ethereum and Hyperledger include sophisticated scripting languages to model complex interactions for different kinds of native (i.e., embedded in the blockchain) and tokenized (i.e., asset value fragmented into crypto tokens) assets. Second, this issuance of asset-backed tokens (referred to as tokenization) is enabled by BT and the overlying smart contracts. BT can thus store and transmit transactions to include asset classes, such as intangible or fungible assets (e.g. patents, electricity) or rights associated with an asset (e.g. digital media). In addition to financial transactions, experts particularly expect a rise of identity-related, property, and communication-based transactions (Hileman, 2017). The possibility to tie different kinds of information to a transaction not only broadens the application scope of BT but makes it a highly versatile medium for general information processing.

2.2 Smart cities

Under current predictions, 70% of the world's population will live in cities by 2050 (United Nations, 2016). The increasing trend towards urbanization creates various problems as cities are a major cause of environmental degradation and raise novel societal and institutional challenges (Kramers, Höjer, Lövehagen and Wangel, 2014; Lövehagen and Bondesson, 2013). These issues call for novel solutions that enable cities to organize in novel, "smarter" ways to ensure an adequate infrastructure, environment, and life quality of citizens (Chourabi et al., 2012).

In this context, the term "smart city" was introduced in the 1990s (Cocchia, 2014). Due to the newness and boundary-spanning nature of the concept, a consistent definition has not yet been established (Komninos et al., 2013; Ojo, Curry and Janowski, 2014). After reviewing 46 definitions in different domains, Nam and Pardo (2011) differentiate between three core perspectives on smart cities: institutional, human, and technology. The institutional perspective encompasses policy reworks, changes in government structures and the creation of smart communities as vehicles for sustainable urban transformation (Moss Kanter and Litow, 2009), while the human perspective emphasizes investments in innovativeness and learning (Boulton, Brunn and Devriendt, 2011; Glaeser and Berry, 2006). The technological perspective focuses on how ICTs can be leveraged to make cities work smarter (Kramers et al., 2014). The latter perspective on smart cities forms an essential building block of the emerging Green IS research stream (Melville, 2010; Watson, Boudreau and Chen, 2010).

As the boundary-spanning nature and importance of ICTs are key characteristics of smart cities, this study follows Washburn et al. (2009, p. 2) who define smart cities as "the use of smart computing technologies to make the critical infrastructure components and services of a city – which include city administration, education, healthcare, public safety, real estate, transportation, and utilities – more intelligent, interconnected, and efficient." ICT-enabled systems and infrastructures create value through savings in time, emissions and energy, and through positive externalities via the stimulation of the economy, innovation, and citizen engagement (Manville et al., 2014). In practice, smart cities apply ICTs in a range of interoperating (hybrid) layers, from physical infrastructure and integration layers like smart grids, sensor technology, and cloud services to pure service applications (Granath and Axelsson, 2014).

3 Methodology

To address our research question, we develop a taxonomy of blockchain-based smart city applications offered by startups. Taxonomies are schemes that allow for the grouping of objects. They offer a structured approach to describe and classify existing or future objects of interest, thereby providing order in complex areas (Nickerson, Varshney and Muntermann, 2013). Especially in the case of novel phenomena—such as the use of BT in the smart city context—taxonomies provide valuable insights as they help understanding, analyzing, and structuring extant domain knowledge (Nickerson et al., 2013) and generate more solid concepts on which future research can build upon (von Krogh, Rossi-Lamastra and Haefliger, 2012). Particularly in the fast-changing domain of information systems (IS), classifying objects into taxonomies is a useful and important research method (Son and Kim, 2008; Williams, Chatterjee and Rossi, 2008).

3.1 Data collection

First, we gathered data on startup firms that offer blockchain-based smart city innovations. Startups are known for developing novel, high-risk, and cutting-edge ideas and are likely to be first movers regarding innovative technologies (Chesbrough, 2006; Freeman and Engel, 2007; Weiblen and Chesbrough, 2015). For this reason, blockchain taxonomies tend to focus on startups (Eickhoff, Muntermann and Weinrich, 2017; Gimpel, Rau and Röglinger, 2017). Accordingly, we focus on startups to analyse how blockchain can be used for achieving smart city objectives. Our data collection included global startups in different investment stages—from seed to series A.

We collected the data using two databases of technology startups, curated by CrunchBase (www.crunchbase.com) (last update: June 30, 2018), Blockchain Angels (www.blockchainangels.eu) (last update: June 30, 2018), and Outlier Ventures (www.outlierventures.io) (last update: March 10, 2019). CrunchBase provides various information on more than 500,000 general purpose startup ventures while Blockchain Angels allows to filter for Blockchain startups, covering 1,245 startups. Third, Outlier Ventures provides a blockchain startup tracker that comprises 1,350 startups.

In the CrunchBase database, the search term “blockchain” yielded 482 startups. We first eliminated duplicates and startups that do not offer solutions for the smart city core areas of administration, education, healthcare, public safety, real estate, transportation, or utilities (Washburn et al., 2009). From the initial set of startups (n = 3,077), 438 startups remained in the sample. Second, we excluded startups that focus on general blockchain infrastructure including the hardware and fabric layer upon which the application layer builds (Glaser, 2017). The resulting sample consisted of 163 startups. Third, we considered only startups for our analysis that were actually in operation at the time of our search and for which sufficient information for classification was publicly available (e.g. websites, press releases). In several instances, we additionally reached out to startups to gather additional information. This procedure resulted in a final sample of 80 startups (see Appendix A).

3.2 Taxonomy development

To develop our taxonomy, we follow the methodological guidelines provided by Nickerson et al. (2013) as depicted in Figure 1. In the first step, a meta characteristic is determined. A meta characteristic is “the most comprehensive characteristic that will serve as the basis for the choice of characteristics in the taxonomy” (Nickerson et al., 2013, p. 343). When determining the meta characteristics, the taxonomy’s purpose and the interests of its future user group has to be acknowledged. Therefore, our study’s meta characteristic is defined as the application of BT in smart city areas. This definition complies with the purpose of our taxonomy, namely to identify the potential uses of blockchain in smart cities encompassing both business- and technology-related attributes.

In the second step, objective and subjective ending conditions need to be determined. The eventual taxonomy is composed of layers that combine related dimensions and their modes of occurrence, labelled characteristics. As the compilation of dimensions and corresponding characteristics occurs iteratively, the researcher must define conditions that will indicate the completeness of the taxonomy beforehand. Objective ending conditions are the uniqueness of each characteristic and dimension and that at least one object falls into the category of each characteristic and dimension included in the taxonomy (Nickerson et al., 2013).

The subjective ending conditions require the taxonomy to be concise, robust, extendible, and explanatory. Although we avoided redundancies in our choice of characteristics, the taxonomy’s application on our sample revealed that in some instances several characteristics can be applied. However, this outcome does not violate the taxonomy properties as the alternative would be an inflated set of characteristics (Püschel, Röglinger and Schlott, 2016). We checked the ending conditions before finishing the iterations.

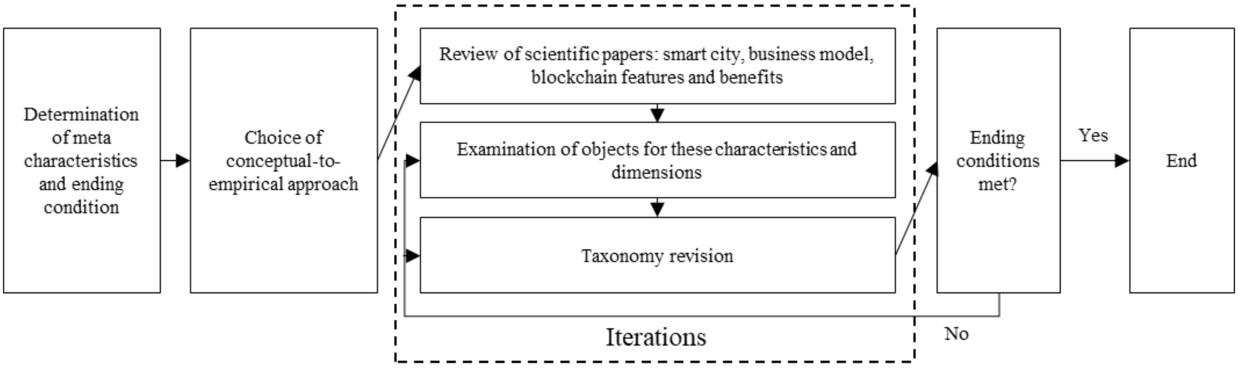

Figure 1. Research approach for smart city blockchain application taxonomy development.

As a third step, Nickerson et al. (2013) recommend to choose either a conceptual-to-empirical or an empirical-to-conceptual taxonomy development procedure. In the conceptual-to-empirical approach, the researcher determines the taxonomy's dimensions using "his/her knowledge of existing foundations, experience, and judgment to deduce what he/she thinks will be relevant dimensions" (Nickerson et al., 2013, p. 346). The researcher then tests the relevance of the chosen dimensions and characteristics by examining objects. If no object can be grouped into these dimensions and characteristics, they should be eliminated. By contrast, in the empirical-to-conceptual approach, the researcher starts with examining actual objects by identifying a subset of objects to be classified and then grouping the objects according to common dimensions with discriminating characteristics. Both approaches are highly iterative, meaning that dimensions and characteristics are constantly added, deleted, merged, or split.

For this study, we chose a conceptual-to-empirical approach. During the first iteration, we defined the taxonomy dimensions based on various approaches to smart city areas, business models, and BT features in order to determine characteristics of structural difference in the subsequent iterations. We performed several iterations on the basis of our sampled startups until we were not able to identify any further characteristics. In the following iterations, characteristics for the dimensions were therefore continuously added, edited and consolidated. After each round, we revised the taxonomy through an expert panel (3 researchers, 3 practitioners) to assure the taxonomy's validity. As a result, we were able to classify all startups and meet the ending conditions as proposed by Nickerson et al. (2013).

4 Results

Our final taxonomy consists of three layers. In the first layer, *smart city application area*, we identified five smart city areas in which startups operate. The business model layer comprises five dimensions along the sub-layers value proposition, value delivery, and value capture. The blockchain application layer comprises dimensions that refer to technological attributes of the startups' solutions.

4.1 Smart city application area

We assigned each startup in our sample to one or more smart city application areas and, more specifically, to a role within this area. Overall, we find the highest number of startups in the government domain (n = 21) and energy domain (n = 20), followed building (n = 16), health (n = 15), and transportation (n = 10).

Smart city application area	***Energy***	P2P transaction platform	Corporate energy transactions	Crowdfunding platform	Carbon asset management	Science & research
	Transportation	Ride sharing	Tolls	Parking	PEV charging	Container logistics
	Building	Property transactions	Energy consumption	Funding	Building access authorization	
	Health	Patient records	Pharmaceutical authenticity verification	Research data provision	Emergency alerts	Digital nudging
	Government	Registry services	Voting	Donation tracking	Citizen dialogue	Digital citizenship

Figure 2. Smart city application areas of blockchain-based smart city applications.

4.1.1 Energy

Our sample includes energy blockchain startups in five categories. A core aim of the smart city concept is that energy is produced and consumed as efficient and sustainable as possible. Blockchain startups address these goals in several ways. First, blockchain is used to enable peer-to-peer transactions between consumers and the tracking of energy units, especially those generated by renewables. First, blockchain is used to enable peer-to-peer transactions between consumers and the tracking of energy units, especially those generated by renewables. Startups such as LO3 and GridSingularity offer blockchain-based peer-to-peer energy distribution which allows prosumers to convert their energy surplus into energy tokens that they can price themselves and sell locally to other consumers. Another way of using blockchain for energy efficiency is to generate energy coins that reimburse leases for solar systems given to private persons or businesses in developing countries via crowdfunding platforms (e.g. SunExchange). We further identified startups that use blockchain to act as transaction platforms for energy stakeholders including traditional corporate suppliers (e.g. OmegaGrid), as well as startups that support solutions for scientific research (e.g. ElectricChain) or carbon asset management (e.g. Energy Blockchain Lab).

4.1.2 Transportation

In the area of transportation, we identified five categories. The startup Oaken Innovations enhances automotive sensor capabilities by integrating blockchain-enabled nodes, which can automatically pay tolls for usage of roads or bridges. In addition, applications based on BT may soon fully decentralize peer-to-peer car sharing models (Pick and Dreher, 2015). In our sample, the startups Arcade City, Chasyr, and La'Zooz are launching P2P ride sharing services that operate on a trustless basis, making intermediaries like Uber or Lyft obsolete. Users can access ride offers through the public transaction book and trade in proprietary tokens. In the field of transportation, blockchain startups further address issues of parking (e.g. Parq) and solutions for plug-in electronic vehicle (PEV) charging (e.g. Slock.it). Powertree's approach addresses private persons who are willing to make their house's grid available for passing PEV users for a fee that is paid via smart contracts.

4.1.3 Building

Several startups address issues related to buildings' energy consumption. To overcome privacy concerns regarding metering and optimizing energy consumption (Kranz, Gallenkamp and Picot, 2010), BT is used to store the data anonymously and securely. The startup Ubirch offers sensors that connect to a digital platform which allows users to track consumption and reduce their energy costs using blockchain for encryption. Similarly, Silvertown sources data regarding temperature, humidity and noise levels, air quality and motion from smart beacons to assist housing associations and large property managers with metering. Manual readings become obsolete and blockchain ensures data integrity and privacy of tenants.

Another area tackled by startups are smooth and secure real estate transactions. Startups use BT to verify users' identities, making mediators like realtors obsolete while ensuring cheaper, faster and more reliable transactions. BT is further used as a crowdfunding and tokenized ownership solution by the startups to enable buyers to take out loans from private or business investors through smart contracts. Another application area of BT is to verify persons who try to access buildings (e.g., Slock.it).

4.1.4 Health

Blockchain may emerge as a key enabler of e-health solutions that improve the quality and accessibility of diagnosis and treatment in smart cities. We identified various solutions that enable various stakeholders including patients, payers, health apps, and hospitals to combine health data on the blockchain via secured APIs. Further, some startups provide the option to make the data accessible to scientists, leading to a crowdsourced approach to medical research. Beside initiatives in the fields of diagnosis and treatment, blockchain is also used to authenticate pharmaceutical supply chains to mitigate the risk of pharmaceutical counterfeits (e.g. Blockpharma). Due to its fraud-resistant technology, startups use blockchain to register pharmaceutical fabrications throughout the supply chain all the way to the end consumer. BT is further used for digital nudging by providing reliable token systems that reward persons for healthy behaviors. HealthCoin, for instance, offers a blockchain-based diabetes prevention application which allows insurers or employers to reward health conscious lifestyles based on biomarker indications. The startup DAERS offers a decentralized autonomous emergency reporting system which stores vital signs and GPS location information on the blockchain. This information can be accessed by authorized international organizations or rescue units in case of emergency.

4.1.5 Government

Blockchain technologies may contribute to more user-friendly public services, improved transparency, and the elimination of corruption (OECD, 2017). We identified five categories of blockchain startups in the government application area. A number of startups offer registry services, e.g. for taxes, property titles, or other identity documents especially regarding land titles, many startups are emerging such as BitLand Global in Ghana. In countries that are troubled by instable governments, a weak rule of law or political disputes, blockchains offer a reliable way of storing land titles. Beside registry services, smart city applications use blockchain for voting and citizen engagement. Regarding e-voting, the advantages of blockchain technologies stem from its authentication abilities and the possibility to store votes securely and make elections more transparent. To enhance citizen dialogue, the anonymity and disintermediation enabled by BT is used for citizen engagement. For instance, the startup MiVote enables citizens to submit a vote for upcoming parliamentary elections, thereby giving politicians and the media the ability to get an accurate picture of popular opinions. Another area in which BT can contribute to smarter governments relates to the tracking of donation funds. As blockchain tokens or currencies can be traced easily, many enable that donors can track their donations. Finally—and perhaps most radically—blockchain startups provide digital citizenships. Based on the idea that every individual is provided with a digital identity, a concept that is being introduced in Estonia (Anthes, 2015) the startups BitNation and Borderless are offering digital citizenship including self-determined constitutions.

4.2 Business model

A business model describes how a firm creates, delivers and captures value (Osterwalder and Pigneur, 2010; Teece, 2010). As the very nature of smart cities is to overcome industry boundaries and to link various infrastructures and stakeholders (Mulligan and Olsson, 2013), the business model concepts provides a useful framework for analyzing how blockchain enables ecosystem-based value creation in smart cities. Blockchain's effects on business models has recently gained attention. Studies envision that the logic of value proposition and value capture may alter or even disrupt industries in the near future as a consequence of blockchain integration (Holotiuk, Pisani and Moormann, 2017; Iansiti and Lakhani, 2017).

Business model	***Value proposition***	***Primary blockchain benefit***	Security by design	Auditability	Smart contracts	Micro-transactions	Disintermediation	User verification	Data reconciliation speed	Tokenization	Anonymity
	Value delivery	***Customer type***	Consumers	Prosumers	Businesses	Governments					
		Product composition	Cyber-physical	Purely digital							
	Value capture	***Revenue model***	Free	Freemium	Fee-based	Subscription	Upfront payment				

Figure 3. Business models of blockchain-based smart city applications.

4.2.1 Value proposition

The second part of the business model layer examines in which ways the offers of blockchain startups create unique value for their customers, i.e., helping customers to perform a particular job better than alternative offerings (Johnson, Christensen and Kagermann, 2008).

Primary blockchain benefit

One major benefit offered by blockchain startups is the reduction of transaction costs which result from uncertainty or unforeseen contingencies and from writing and enforcing contracts (Tirole, 1999). We distinguish between three core benefits of BT with regard to transaction cost reduction (security by design, auditability, and smart contracts). Blockchains are secure by design as the decentralized ledger renders entries tamper-proof (Zyskind and Nathan, 2015). Especially startups in government registry services, voting, and house access solutions benefit from this feature. Auditability refers to the transparency afforded from blockchain's ability to review past entries and a token's history (Davidson et al., 2016; Orsini, Wei and Lubin, 2016). We find that auditability is primarily exploited by startups in the areas of donation tracking, pharmaceutical authentication, voting, and logistics. Smart contracts reduce transaction costs because expenses related to writing and enforcing contracts are significantly lowered (Kiviat, 2015). Smart contracts are particularly effective regarding lowering transaction costs when transactions are highly standardized and occur frequently as in the energy sector (e.g., SunExchange, LO3) or when they occur between parties otherwise unknown to each other as in ride sharing or real estate funding.

Further blockchain-specific benefits are disintermediation (which in some instances is a consequence of lower transaction costs), user verification, micro transactions, speed, tokenization, and anonymity. Disintermediation is especially prevalent in peer-to-peer business models that render previous mediator platforms obsolete. User verification plays a main role in voting and registry startups as user identification is critical in these domains. Further, BT facilitates micro transactions which are often used in the energy and transportation area. Speed in data reconciliation is another blockchain-specific benefit arising from our analysis. For instance, energy startups can provide accurate and close to real-time data on consumption and generation. Tokenization refers to the possibility of issuing cryptographic tokens on the blockchain, to be incorporated in the business model. Finally, we elicit that business models profit from the anonymity BT grants which is a core asset in citizen dialogue, medical research or automated energy metering.

4.2.2 Value delivery

Value delivery describes the apparatus an organization sets up to deliver value (Teece, 2010). Our taxonomy shows how startups use blockchain to deliver value analyzing customer types and product composition.

Customer type

The dimension customer type captures to whom a firm markets its product. Digital technologies have led to a shift towards direct company-customer interaction throughout industries (Wikström, 1996). BT in particular has facilitated niche products targeting small, technology-minded communities (Malović, 2014). We find that the startups in our sample also cater to both businesses and end customers. Startups further address individual professionals such as doctors or solar scientists. BT is often related to disintermediation. Blockchain systems promote P2P transactions and enable novel prosumer markets. We find P2P startups specifically in the smart city areas energy and transportation. Energy P2P-platforms such as Sonnen enable to purchase green electricity from peers without using existing electricity grids. Moreover, governments are addressed by blockchain-based smart city startups. For example, Bitfury is working on a registry of land titles for the Republic of Georgia (Underwood, 2016). In addition, voting providers like Voatz are collaborating with municipalities and federal government units. In addition, governments are involved in blockchain-based healthcare business models to settle processing claims and ensure smooth healthcare transactions.

Product composition

Another important dimension emerging from our analysis is whether an offer is composed of physical and software components (cyber-physical) or is purely digital, hence intangible. With increasing levels of digitization, an increasing number of physical products is equipped with software (e.g., sensors or actuators) that allow for new value-added services such as monitoring and control. Blockchain-based applications can occur in digital or cyber-physical forms. Most startups provide digital solutions. In these instances, BT itself provides sufficient value and acts independently of physical assets. However, we also identify several startups that process data from physical objects, often provided by the startup itself. For example, Oaken Innovations recently turned a Tesla into a smart vehicle that automatically pays via the cryptocurrency Ether at toll gates. Further, real estate startups market cyber-physical systems that convey verification or usage data by using blockchain technologies.

4.2.3 Value capture

The last dimension of the business model layer concerns the type of value capture mechanism, which is a main aspect of an organization's business model (Osterwalder, Pigneur and Tucci, 2005). It describes how an organization extracts value from its operations, enabling sustainable operations. We find that smart city blockchain startups have found various ways to capture value. Subscription models are prevalent in government registry and healthcare solutions. Voting and citizen dialogue startups tend to operate on a free or freemium basis. The startups that enable transactions in real estate, energy and transportation predominantly use a fee-based approach. Business models for cyber-physical products combine upfront payments for hardware with subscription or fee-based payments during utilization.

4.3 Blockchain application

In the third layer of our taxonomy, we consider how startups apply the BT from a technical perspective. We refer to the technical setup in two sub-layers, the permission model and protocol provider.

<table>
<tr><td rowspan="3">Blockchain application</td><td rowspan="2">Permis-sion model</td><td>Reading</td><td colspan="3">Public</td><td colspan="2">Private</td></tr>
<tr><td>Writing</td><td colspan="3">Permissionless</td><td colspan="2">Permissioned</td></tr>
<tr><td colspan="2">Protocol provider</td><td>Bitcoin</td><td>Ethereum</td><td>Hyperledger</td><td>Bitshares</td><td>Other/proprietary</td></tr>
</table>

Figure 4. Blockchain application of blockchain-based smart city applications.

4.3.1 Permission model

System centralization is concerned with "the extent to which a network is evenly distributed or nuclear in terms of ownership and administration" (Walsh et al., 2016, p. 3). The question of centralization addresses two kinds of permission restrictions: permission to read and to write (Walsh et al., 2016; Xu et al., 2017).

Reading permissions

On a public blockchain, there are no restrictions on reading blockchain data, while only predefined users can read the data on a private blockchain. The advantages of using a public blockchain are better information transparency and auditability, while performance and information privacy is sacrificed (Xu et al., 2017). We find that most of the startups in our sample rely on public blockchains, therefore satisfying the desire for transparency and auditability. Especially voting startups emphasize their added value from being publicly accessible, rebuilding trust in election results. These arguments are also valid for applying public blockchains in the application areas donation tracking, land titles, energy, and transportation. We find private blockchains in areas where data privacy is critical, such as in healthcare and government registry services that involve identity solutions.

Writing permissions

In terms of permission restrictions related to writing, the eligible processors can either be predefined (permissioned) or unrestricted (permissionless). Services with a single provider in regulated industries, such as governments or courts, are examples of permissioned technologies (Xu et al., 2017). The choice of verifier permission scope is bound to tradeoffs in terms of transaction processing rate, cost, censorship resistance, reversibility, finality, and flexibility (Xu et al., 2017). In the startups of our sample we find a tendency for permissionless networks. The reason is that permissionless verification is combined with the independence of random processors, for example in voting and citizen dialogue startups or energy data transaction platforms. We find permissioned networks registry, health, and property transaction in cases in which verification processes are executed in controlled environments to guarantee formality of the entries.

4.3.2 Protocol provider

Blockchain applications run on a specific protocol which form the foundation for its functionalities (Morabito, 2017a). We found startups building upon the Bitcoin blockchain in all smart city areas, except transportation. However, the by far most commonly used protocol is the public Ethereum blockchain. Startups from all smart city areas in our sample build upon Ethereum. Moreover, smart city blockchain startups frequently build upon the Hyperledger and Bitshares platforms. Hyperledger is an initiative led by the Linux Foundation in cooperation with companies like IBM, Airbus and Samsung to explore the possibilities of private blockchains (Morabito, 2017b). Our sample shows that startups in the areas energy and health use Hyperledger. Bitshares, on the other hand, is a trade-centric platform that is mainly used to exchange securities and financial instruments like derivative contracts. Moreover, some startups of our sample use proprietary platforms or specialized computing platforms such as Multichain, Expanse, and Tierion.

5 Discussion

From our in-depth analysis of 80 global startups offering BT-based solutions for smart cities, we identify three major implications of how BT can contribute to building smart cities. We found that BT (1) triggers novel models for the sharing economy, (2) creates solutions regarding privacy and security of citizens, governments, and businesses, and (3) enables the improved applications in the Internet of Things (IoT).

Sharing economy is characterized as "collaborative consumption made by the activities of sharing, exchanging, and rental of resources without owning the goods" (Lessig, 2008, pp. 143 ff.). Our taxonomy shows that various startups develop applications that increase the efficiency of the sharing economy at the process level in which “consumers, providers and intermediaries are connected by different types of process categories” (Puschmann and Alt, 2016, p. 96), particularly regarding contracting, billing, and fulfillment. Hence, BT enables agents to act autonomously with close-to-zero transaction costs and following a set of rules provided by smart contracts. As such, agents will be able to act autonomously and they will coordinate complying with pre-defined rules. Therefore, blockchain-based sharing economy systems can operate at close-to-zero transaction costs. Startups that engage in this domain will commonly fulfill the following main characteristics in our developed taxonomy. BT alters the way that market sides interact. Since the elimination of intermediaries is a central characteristic of the sharing economy, disintermediation is a primary blockchain benefit in this domain. The majority of sharing economy startups also incorporate decentralization in their technological setup. As such, these startups typically choose public and permissionless blockchains. We find startups that use BT for sharing economy business models mainly in the smart city areas energy, transportation and buildings.

We found that many startups in the smart city domain leverage BT’s potential to provide privacy- and security-preserving products and services. BT is secure by design as it provides a secure distributed ledger of transactions. In comparison to centralized systems, blockchain’s distributed architecture has no single point of failure increasing trust in the system and data security as its functioning does not depend on a single intermediary or a restricted number of participants (Nofer, Gomber, Hinz and Schiereck, 2017). Several startups build upon the security by design property as a main blockchain attribute. Further, most of these startups follow a centralized network approach with private reading mechanism and a pre-determined set of processors (permissioned writing). We observed that startups offer privacy and security solutions particularly in the smart city areas voting, registry services, patient record, container logistics, and pharmaceutical authenticity verification.

We can further observe startups in the domain of IoT, connecting the physical to the digital world by equipping physical objects with sensor and communication technology to integrate them via the internet. As these cyber-physical objects need to communicate securely and to transact value in general or money in particular, BT seems to be a natural fit (Christidis and Devetsikiotis, 2016). In an IoT environment, cyber-physical objects with the appropriate hardware can be connected to a blockchain. This enables sending and receiving small amounts of money such as a few cents between objects without risks of man-in-the-middle attacks and always with a proven fact that a specific transaction in question has been initiated by a specific device, thus ruling out fraud. Typical characteristics for the IoT domain include micro transactions and cyber-physical products. Startups in the IoT domain typically utilize smart contracts to facilitate instantaneous transactions on multi-sided markets. In the smart city context, IoT startups are typically found in transportation as well as energy- and utility-related markets.

Finally, we need to point to a couple of limitations which should be addressed by future research. The process of taxonomy development in general presents the quest for a useful rather than optimal solution (Nickerson et al., 2013). Thus, we encourage researchers to build on, extend, or adapt our results. Moreover, many of the examined startups can offer their products or services to customers irrespective of population density. Thus, the startups in our sample are not necessarily focusing on urban environments, but on providing a solution for an urgent urban need or performing a useful activity in the smart city context. As Nickerson et al. (2013) state, a useful taxonomy is extendable. Dimensions and characteristics may be added as the studied field grows or assumes new shapes. This attribute seems especially valuable in our context as many of the examined startups are in early stages, business and technological characteristics will be subject to dynamic change.

6 Conclusion

This study aimed at providing insights on the intersection of two emerging topics in IS research—BT and smart cities. For this purpose, we developed a taxonomy that points out the manifold fields of how BT is applied in the smart city context. The taxonomy shows how BT enables and impacts business models and which technological architectures are used. Our contribution to the IS literature is twofold.

First, we investigate an emerging phenomenon on which research is scarce. In the spirit of a "phenomenon-based research strategy" (von Krogh et al., 2012), we explored a new phenomenon by describing and classifying blockchain-based smart city applications. Thereby the study provides a structure in a complex domain and may serve as a basis for further theorizing (von Krogh et al., 2012). Second, we contribute to research on IT-enabled and digital business models (Veit et al., 2014) as we show how a digital innovation like BT is used to transform consumer behavior and society. Particularly, we provide insights on how blockchain shapes the delivery, creation, and capture of economic value.

Overall, we find that smart cities can greatly benefit from the unique advantages of BT. Given that the majority of current (and future) mega cities is located in developing countries where unstable governments and unreliable utility infrastructure are prevalent, the decentralization that blockchain offers in respect to secure data storage and new ways of utility management could improve the life quality of several hundreds of million people. Equally, city dwellers and governments in developed nations make use of blockchain-enabled IoT, security, and sharing economy solutions. At a time when trust in government institutions and corporate intermediaries is frequently shattered (GALLUP, 2016; Mayer, 2013) BT can reestablish trust, and contribute to more independent and active citizenship–especially, but not limited, to countries with weak institutions and instable regimes.

However, the usage of blockchain technologies in smart cities may also leads to new challenges, for example with respect to governance. It remains an open question how BT will be predominantly deployed and governed in a smart city environment. Similar to Bitcoin, which simultaneously facilitates community-based P2P payments and centrally governed digital currencies, BT applications in smart cities may originate from community-based P2P focused initiatives or from broader government or private sector initiatives. Both modes of deployment and governance may ultimately prove to be highly compatible. While P2P initiatives facilitate spontaneous, local and dynamic markets for economic, social or political activities (conceptually captured by the idea of catallaxies; Davidson et al., 2016; Hayek, 1960; Lubin, 2016), the system-wide integration of single activities on a city, country or even global level will be necessary to realize larger efficiency gains and overarching goals (e.g. reduction of carbon emissions). Technically this may lead to a mesh of blockchains (e.g. energy and mobility blockchains) and will require solutions facilitating blockchain interoperability. On a technological level, scalability is another challenge to the dissemination and efficiency of blockchain solutions in smart cities. Rigid infrastructures and costly mining processes restrict the usefulness of blockchains on a greater scale. However, developed ledger technologies such as used by IOTA can mitigate these problems.

Appendix

Smart city application area	Startups (country)
Energy	• Bankymoon (ZA) • Dajie / Prosume (UK) • ElectricChain (AD) • Jump Software (USA) • SolarChange (ISR) • MyBit (CHE) • Electron (USA) • Energy Blockchain Lab (CHN) • Grid Singularity (AUT) • LO3 (USA) • TerraLedger / Volt-markets (USA) • Smappee (USA) • Solether (n/a) • Batan (UK) • Omega Grid (USA) • Sonnen (USA) • SunExchange (ZA) • Sunride (GER) • Wattcoin (USA) • Consensys (USA)
Transportation	• Arcade City (USA) • T-Mining (BEL) • Chasyr (USA) • Oaken Innovation (USA) • Parq (NL) • Powertree (USA) • La'Zooz (ISR) • Parkgene.io (GRC) • Cloudpark (USA) • Slock.it (DEU)
Building	• Ubirch (DEU) • HomeSidekick (USA) • Propy (USA) • Propify / Coicio (USA) • Silvertown (UK) • Slock.it (DEU) • Ubitquity (USA) • Blocksquare (SVN) • Tapclose (USA) • Flip (USA) • BrikShares (IT) • Smappee (USA) • Cleverent (USA) • REIDAO (SGP) • REX (USA) • Realblocks (USA)
Health	• Blockpharma (FR) • BurstIQ (USA) • DAERS (CH) • Hashed Health (USA) • Patientory (USA) • Health Chain (UK) • SimplyVital Health (USA) • Open Health Network (USA) • Healthcombix (USA) • PointNurse (USA) • Betternot.rest (BRA) • GEM (USA) • Health Wizz (USA) • Healthcoin (USA)
Government	• Advocate (USA) • BitFury (USA) • Bitland Global (GH) • Follow My Vote (USA) • Neocapita (AUT) • Votem (USA) • PlaceAVote (USA) • Socioneers (NL) • Voatz (USA) • Disberse (UK) • Helperbit (IT) • Authenteq (DE) • MiVote (AUS) • Crowdesto (UK) • Start Network (UK) • Bitnation (n/a) • Democracy Earth (n/a) • VoteHQ (CAN) • Borderless (n/a) • Procivis (CH) • BitGive Foundation (USA)
(n/a) expresses startups that do not provide a registered office	

Appendix A: Sample structure

Smart city application area	***Energy*** (24%)		P2P transaction platform (32%) [10%]	Corporate energy transactions (32%) [10%]	Crowdfunding platform (24%) [8%]	Carbon asset management (8%) [2%]	Science & research (4%) [1%]				
Smart city application area	***Transportation*** (12%)		Ride sharing (27%) [4%]	Tolls (9%) [1%]	Parking (36%) [5%]	PEV charging (18%) [2%]	Container logistics (9%) [1%]				
Smart city application area	***Building*** (20%)		Property transactions (47%) [10%]	Energy consumption (18%) [4%]	Funding (29%) [6%]	Building access authorization (6%) [1%]					
Smart city application area	***Health*** (18%)		Patient records (50%) [13%]	Pharmaceutical authenticity verification (9%) [2%]	Research data provision (23%) [6%]	Emergency alerts (5%) [1%]	Digital nudging (14%) [4%]				
Smart city application area	***Government*** (26%)		Registry services (22%) [6%]	Voting (26%) [7%]	Donation tracking (22%) [6%]	Citizen dialogue (17%) [5%]	Digital citizenship (13%) [4%]				
Business model	***Value proposition***	***Primary blockchain benefit***	Security by design (15%) [40%]	Auditability (17%) [45%]	Smart contracts (18%) [50%]	Micro-transactions (10%) [27%]	Disintermediation (13%) [37%]	User verification (7%) [18%]	Data reconciliation speed (10%) [27%]	Tokenization (6%) [17%]	Anonymity (4%) [12%]
Business model	***Value delivery***	***Customer type***	Consumers (37%) [61%]	Prosumers (13%) [22%]	Businesses (35%) [57%]	Governments (14%) [23%]					
Business model	***Value delivery***	***Product composition***	Cyber-physical (32%)	Purely digital (68%)							
Business model	***Value capture***	***Revenue model***	Free (20%) [22%]	Freemium (2%) [2%]	Fee-based (33%) [35%]	Subscription (34%) [37%]	Upfront payment (10%) [11%]				
Blockchain application	***Permission model***	***Reading***	Public (82%)	Private (18%)							
Blockchain application	***Permission model***	***Writing***	Permissionless (74%)	Permissioned (26%)							
Blockchain application	***Protocol provider***		Bitcoin (11%)	Ethereum (59%)	Hyperledger (5%)	Bitshares (2%)	Other/proprietary (23%)				

(…): relative ratio, […]: absolute ratio

The absolute ratio is the number of occurrences per characteristic related to the number of startups in the sample.
To ensure comparability for non-exclusive dimensions, we in those cases additionally calculated the relative ratio, which relates the number of occurrences per characteristic to the total number of occurrences per dimension.

Appendix B: Classification results

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