Smart City Applications on the Blockchain: Development of a Multi-layer Taxonomy

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Abstract Blockchain Technology (BT) has become widely recognized beyond the financial sector. Various other fields of application for the ground-breaking innovation are discussed by researchers and practitioners alike. One such field is the smart city. Driven by startups, projects aimed at alleviating negative effects of urbanization build on the properties of BT to improve quality of life, administrative processes, and environmental sustainability. Yet, due to the entrepreneurial dynamics and abundant fields of application for BT in smart cities, an integrated and boundary-spanning analysis is lacking. This study aims at developing a multi-layer taxonomy that illustrates how BT is used in different smart city business models. For this purpose, we identified a sample of 80 startups which offer applications for smart cities and examined their business models. The paper explores business model configurations and technological characteristics of blockchain-based smart city applications. We identify BT startup archetypes in several domains: sharing economy, privacy and security, and internet of things (IoT). The paper will be useful for researchers, practitioners, and regulators interested in gaining novel insights about how startups leverage BT to create and capture value.

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

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distributed with a consensus mechanism that replaces a central point of control (Beck et al. 2016). Prior to BT, an intermediary was needed to control, maintain, and oversee databases and networks. Due to new consensus mechanisms, a blockchain enables every network member to contribute to the network and work as a control instance (Davidson et al. 2016). With first use cases in finance and banking, the technology is triggering game-changing applications in further sectors. Because of their decentralized nature and potential for automation, smart cities are an important field of application for 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 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 in order to use resources more sustainably and efficiently (Harrisson 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 and societal implications of using BT. Prior taxonomies have examined BT in the fields of governance and architecture (Glaser 2017; Xu et al. 2017), fintech (Beinke et al. 2018), entrepreneurial finance (Chanson et al. 2018; Fridgen et al. 2018; Kazan et al. 2015; Kranz et al. 2019), and general applications (Labazova et al. 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. Therefore, we analyzed business models and technological features smart city applications. Our economic and technological perspective allows to assess how the pieces of a business (Magretta 2002) and a technology fit together to create, deliver, and capture value.

To achieve this goal, we analyzed in-depth how startups in the smart city context build upon BT to increase the efficiency, sustainability, and quality of life in urban agglomerations. Therefore, we consider solutions for the smart city core areas energy, transportation, building, health, and government (Komninos et al. 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). Based on our analysis, we identify three primary archetypes of BT startups, i.e., sharing economy, privacy and security, and the Internet of Things (IoT). These archetypes leverage BT's primary benefits, such as automation via smart contracts, auditability, and security by design to render value to users.

The remainder of this article 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 and identified archetypes. The chapter concludes with a discussion of the results, limitations, and opportunities for further research.

2 Background

2.1 Blockchain Technology

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 et al. 2016). Beside the consensus mechanism, the chosen permission model is an important distinctive feature of a blockchain. The permission model defines which nodes may read and validate transactions on a blockchain (see Table 1).

Since Nakamoto's original idea of using BT for the cryptocurrency Bitcoin (Nakamoto 2008), BT has gained broader applicability beyond cryptocurrencies and applications in the financial sector owing mainly to two extensions. 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 et al. 2017). To facilitate token issuance and smart contracts, Blockchain protocols like 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

Table 1 Blockchain typology (Beck et al. 2018)

Access to transactions	Access to transaction validation	
	Permissioned	Permissionless
Public	All nodes can read and submit transactions. Only authorized nodes can validate transactions	All nodes can read, submit, and validate transactions
Private	Only authorized nodes can read, submit, and validate transactions	Not applicable

enabled by BT and the overlying smart contracts. BT can thus store and transmit transactions to include further 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 2016). 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. Cities further raise novel societal and institutional challenges (Kramers et al. 2014; Lövehagen and Bondesson 2013). These issues call for innovative 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 et al. 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 et al. 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 et al. 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;

Clohessy et al. 2014). Several studies have pointed towards the substantial opportunities of BT for smart cities arising from improved data reliability and resilience, faster and more efficient operation, and smart-contract-based automation. However, these studies have a narrow focus on particular technological solutions to smart city challenges in fields such as security (Biswas and Muthukkumarasamy 2017), vehicular networks (Sharma et al. 2017), energy (Pieroni et al. 2018), and digital identity (Rivera et al. 2017). We aim to contribute a more comprehensive perspective.

Prior research has studied the features and particularities of business models in smart cities. Timmers (1998, p. 4) defines a business model as “an architecture of the products, services, and information flows”, recognizing stakeholders, business value, and revenue streams as key components of an organization’s operations. Kuk and Janssen (2011) explore how organizations enhance existing services or launch new ones in a smart city context. Other studies have focused on the business model impact of specific technologies, such as mobile telecommunication (Walravens 2015), smart grid solutions (Lee et al. 2010), and big data analytics (Hashem et al. 2016). Smart cities are described as a fertile breeding ground for innovative business models given the interconnection of product streams and information streams as well as fast growing markets (Anthopoulos et al. 2016).

3 Methodology

We developed a taxonomy of blockchain-based smart city business models offered by startups following the guidelines of Nickerson et al. (2013). 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 et al. 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 understand, analyze, and structure extant domain knowledge (Nickerson et al. 2013) and generate more solid concepts upon which future research can build (von Krogh et al. 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 et al. 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). Therefore, blockchain taxonomies have put a focus on the analysis of startups (Eickhoff et al. 2017; Gimpel et al. 2017). Accordingly, we focus on startups to analyze 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 databases of technology startups, curated by CrunchBase (www.crunchbase.com) (last update: June 30, 2018), AngelList (www.angel.co) (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 AngelList allows to filter for Blockchain startups, covering 1245 startups. Third, Outlier Ventures provides a blockchain startup tracker that comprises 1350 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 = 3077), 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 active 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 1), of which some operate in more than one smart city area.

3.2 Taxonomy Development

To develop our taxonomy, we follow the methodological guidelines provided by Nickerson et al. (2013) as depicted in Fig. 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 characteristic, the taxonomy's purpose and the interests of its future user group has to be considered. Therefore, our study's meta

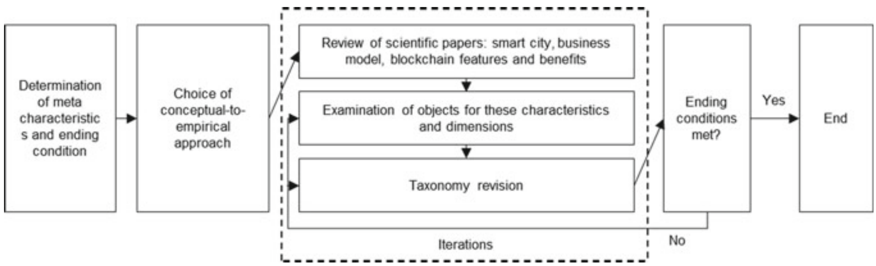

Fig. 1 Taxonomy development based on Nickerson et al. (2013)

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, called 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 include 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 et al. 2016). We checked the ending conditions before finishing the iterations.

As a third step, Nickerson et al. (2013) recommend choosing either a conceptual-to-empirical or an empirical-to-conceptual approach for each iteration of the 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. The researcher identifies a subset of objects to be classified and then groups 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. During this iteration, we defined the taxonomy dimensions based on various approaches to smart city areas, business models, and BT properties in order to determine characteristics of structural difference in the subsequent iterations. We performed several empirical-to-conceptual 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 validity of the taxonomy and the subsequent derivation of archetypes. 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 (see Appendix 1). In the first layer, smart city application area, we identified five smart city areas in which startups operate. The business model layer comprises four 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 area and, more specifically, to a role within this area (Table 2). Overall, we find the highest number of startups in the government (n = 21) and energy domains (n = 20), followed by building (n = 16), health (n = 15), and transportation (n = 10).
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 efficiently and sustainably 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. 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 carbon asset management (e.g. Energy Blockchain Lab) or scientific research (e.g. ElectricChain).

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

Table 2 Smart city application areas of blockchain startups

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

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 rent-seeking intermediaries like Uber or Lyft obsolete. Users can access ride offers through the platform and trade in proprietary tokens. In the field of transportation, blockchain startups further address issues of device identity and payment in parking (e.g. Parq), container logistics (e.g. T-Mining), 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.

Building: Several startups address issues related to buildings' energy consumption. To overcome privacy concerns regarding metering and to optimize energy consumption (Kranz et al. 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 managers of large properties 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).

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 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.

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 in our sample offer registry services, e.g. for taxes, property titles, or other documentation. Especially regarding land titles, many startups are emerging, such as BitLand Global in Ghana. In countries that are troubled by unstable 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 dialogue. 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, startups enable donors to track their donations. Finally—and perhaps most radically—blockchain startups provide solutions for digital citizenships. The concept of digital identity is currently being introduced in Estonia (Rivera et al. 2017). The startups BitNation and Borderless are offering digital citizenship, even 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 concept provides a useful framework for analyzing how blockchain enables ecosystem-based value creation in smart cities (Table 3). BT's effects on business models has recently gained attention. Studies envision that BT integration may alter or even disrupt the logic of value proposition and value capture throughout industries in the near future (Holotiuk et al. 2017; Iansiti and Lakhani 2017).

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 et al. 2008).

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

Table 3 Business models of smart city blockchain startups

Business model											
Value proposition	***Primary blockchain benefit***	Security by design	Auditability	Smart contracts	Disintermediation	User verification	Micro transactions	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				

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 building access solutions benefit from this feature. Auditability refers to the transparency stemming from BT's affordance to review past entries and a token's history (Davidson et al. 2016; Orsini et al. 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, data reconciliation 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 areas. 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.

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

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 environmental 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.

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 allows for new value-added services such as monitoring and control. Blockchain-based applications can occur in digital or cyber-physical forms. Most startups of our sample 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, startups in the 'building' application area are launching cyber-physical systems that convey verification or usage data by using blockchain technologies.

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 et al. 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. 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. Subscription models are prevalent in government registry and healthcare solutions. Business models for cyber-physical products combine upfront payments for hardware with subscription or fee-based payments during utilization.

5 Blockchain Application

In the third layer of our taxonomy, we consider how startups apply BT from a technical perspective. We refer to the technical setup in two sub-layers, the permission model and protocol provider (Table 4).

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).

On a public blockchain, there are no restrictions on reading blockchain data, while only predefined users can read the records on a private blockchain. The advantages of using a public blockchain are better information transparency and auditability, while performance and information privacy are 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, thus rebuilding trust in election results. These arguments are also valid for applying public blockchains in the application areas donation tracking, 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.

In terms of permission restrictions related to writing, the eligible processors can either be predefined (permissioned blockchain) or unrestricted (permissionless blockchain). 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 scope in regard to permissioned verifiers 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 (74%). 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 in cases in which verification processes are executed in controlled environments to guarantee formality of the entries, e.g., in registry, health, and property transactions.

Protocol provider: Blockchain applications run on a specific protocol which forms the foundation for its functionalities (Morabito 2017). We found startups building upon the Bitcoin blockchain in all smart city areas, except transportation. However,

Table 4 Blockchain application of smart city blockchain startups

<table>
<tr><td rowspan="3">Blockchain application</td><td rowspan="2">Permission model</td><td>Reading</td><td colspan="2">Public</td><td colspan="3">Private</td></tr>
<tr><td>Writing</td><td colspan="2">Permissionless</td><td colspan="3">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>

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 2017). Our sample shows that startups in the areas energy and health tend to 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.

6 Evaluation and Archetypes

From our in-depth analysis to develop a taxonomy, three archetypes of blockchain-based business models in the smart city emerged (Table 5). An archetype is a knowledge model which represents commonalities between entities found through prior classification. The determination of archetypes guides theory-led design and supports sense-making in research by emphasizing primary differences among entity types (Püschel et al. 2016; Fernández-Breis et al. 2006). Each of our archetype has a different focus and is linked to specific characteristics assessed in our taxonomy. While these archetypes represent prototypical combinations, we emphasize that the

Table 5 Archetypes of smart city blockchain startups

Business model	Sharing economy	Privacy and security	Internet of things
Description	• Startups providing sharing economy offerings, e.g. in contracting, billing, and fulfillment • Applications allow transactions between consumers and/or prosumers at lower transaction costs, following rules set by smart contracts	• Startups leverage BT's distributed architecture to record and store immutable entries • Ensuring data access only to authorized persons	• Cyber-physical objects store data on a blockchain or record transactions • BT application lower risks such as fraud or man-in-the-middle attacks
Main smart city application areas	• Energy • Transportation	• Government • Health	• Transportation • Building • Energy
Primary blockchain benefit	• Disintermediation • Smart contracts	• Security by design • User verification	• Micro transactions • Smart contracts

archetypes are not mutually exclusive. Emerging blockchain startups tend to combine archetypes in order to assort a unique value proposition and gain a competitive advantage.

6.1 Sharing Economy

The first archetype emerging from our analysis is *sharing economy* which is defined as "collaborative consumption made by the activities of sharing, exchanging, and rental of resources without owning the goods" (Lessig 2008, p. 143). In this archetype blockchain allows to increase the efficiency of sharing economies 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 contracting, billing, and fulfillment. As such, agents will be able to act autonomously and, even more, they will coordinate complying with pre-defined rules. Therefore, blockchain-based sharing economy systems can operate at close-to-zero transaction costs. Startups that follow the archetype sharing economy will commonly fulfill the following main characteristics in our developed taxonomy (see Table 6). The dimension customer type concerns private consumers and/or prosumers that meet on a two- or more-sided market. Since the elimination of intermediaries is a central characteristic of BT-enabled business models in the sharing economy, disintermediation and smart contracts are primary blockchain benefits pertaining to this archetype. The majority of startups belonging to this archetype also incorporates decentralization in their technical setup. As such, these startups typically choose public and permissionless

Table 6 Sharing economy archetype properties. Note. Gray shading shows typical patterns per dimension

<table>
<tr><td colspan="3">Smart city application area</td><td colspan="2">Energy</td><td colspan="2">Transportation</td><td colspan="2">Building</td><td colspan="2">Health</td><td>Government</td></tr>
<tr><td rowspan="4">Business model</td><td>Value proposition</td><td>Primary blockchain benefit</td><td>Security by design</td><td>Auditability</td><td>Smart contracts</td><td>Micro transactions</td><td>Disintermediation</td><td>User verification</td><td>Data reconciliation speed</td><td>Tokenization</td><td>Anonymity</td></tr>
<tr><td rowspan="2">Value delivery</td><td>Customer type</td><td colspan="2">Consumers</td><td colspan="3">Prosumers</td><td colspan="2">Businesses</td><td colspan="2">Governments</td></tr>
<tr><td>Product composition</td><td colspan="5">Cyber-physical</td><td colspan="4">Purely digital</td></tr>
<tr><td>Value capture</td><td>Revenue model</td><td colspan="2">Free</td><td colspan="2">Freemium</td><td colspan="2">Fee-based</td><td colspan="2">Subscription</td><td>Upfront payment</td></tr>
<tr><td rowspan="3">Blockchain application</td><td rowspan="2">Permission model</td><td>Reading</td><td colspan="5">Public</td><td colspan="4">Private</td></tr>
<tr><td>Writing</td><td colspan="5">Permissionless</td><td colspan="4">Permissioned</td></tr>
<tr><td colspan="2">Protocol provider</td><td colspan="2">Bitcoin</td><td colspan="2">Ethereum</td><td colspan="2">Hyperledger</td><td colspan="2">Bitshares</td><td>Other/proprietary</td></tr>
</table>

blockchains. We find startups that use blockchain technology for sharing economy business models mainly in the smart city areas energy and transportation.

6.2 *Privacy and Security*

We found that many startups in the smart city domain leverage BT's potential to provide privacy- and security-affording products and services. Blockchain technology is secure by design as it provides a distributed ledger of transactions. Thus, BT can be regarded as being designed to be secure from the outset. 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 et al. 2017).

In the following, we describe the characteristics of our taxonomy that indicate that startups match with the privacy and security archetype (see Table 7). Startups that belong to this archetype are specialized in the secure storage of entries. Therefore, they rely on the security by design and user verification properties as main blockchain benefits. Further, most archetypal startups follow a centralized network approach with a private reading mechanism and a pre-determined set of processors (permissioned writing). We observed that startups offer privacy and security solutions primarily in the smart city application areas health and government.

Table 7 Privacy and security archetype properties

Smart city application area			Energy	Transportation	Building	Health	Government				
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				
Blockchain application	***Permission model***	***Reading***	Public	Private							
		Writing	Permissionless	Permissioned							
	Protocol provider		Bitcoin	Ethereum	Hyperledger	Bitshares	Other/proprietary				

6.3 Internet of Things

Startups belonging to the Internet of Things (IOT) archetype connect the physical to the digital world equipping physical objects with sensor and communication technology to integrate them via the internet (Yoo 2010; Yoo et al. 2012). As these cyber-physical objects need to communicate securely and to transact value in general or money in particular, blockchain technology seems to be a natural fit (Christidis and Devetsikiotis 2016). In an IoT environment, cyber-physical objects with the appropriate hardware can become part of a blockchain-enabled system. This enables sending and receiving small amounts of money such as a few cents—or even amounts in the sub-cent range—between objects without risks of man-in-the-middle attacks and always with a proof that a specific transaction in question has been initiated by a specific device, thus ruling out fraud.

Typical characteristics for the IoT archetype (see Table 8) include micro transactions, smart contracts, and often a high data entry frequency as IoT systems maintain constant contact with their associated ledger. This relation persists in cyber-physical product compositions. Startups in the IoT archetype typically utilize smart contracts to facilitate instantaneous transactions on multi-sided markets. In the smart city context, IoT startups are typically found in the areas transportation, building, and energy.

Table 8 Internet of Things archetype properties

Smart city application area			Energy	Transportation	Building	Health	Government				
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				
Blockchain application	*Permission model*	***Reading***	Public	Private							
		Writing	Permissionless	Permissioned							
	Protocol provider		Bitcoin	Ethereum	Hyperledger	Bitshares	Other/proprietary				

7 Conclusion

This study aimed at providing insights on the intersection of two increasingly important research topics—blockchain technology and smart cities. For this purpose, we developed a taxonomy that points out the manifold ways in which blockchain technology can be applied in the smart city context. The taxonomy further shows how blockchain technology enables and impacts business models and which technological setup are used. Based on the results of our in-depth analysis, we inferred three archetypes that represent prominent solution approaches.

Our contribution to the 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. Our multi-layer taxonomy reflects the variety of the analyzed sample. We identified three BT-based business models archetypes (sharing economy, privacy and security, and IoT) and delineate how startups in different smart city application areas typically make use of BT. Thus, our study provides structure in a complex domain and can 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 scrutinize how a digital innovation such as BT can be 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 blockchain technologies. Given that the majority of current (and future) mega cities is located in developing countries where unstable governments and unreliable utility infrastructure are prevalent (Kennedy et al. 2014), the decentralization that blockchain offers in respect to secure data storage and new ways of utility management could improve the life quality of millions. 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 runs low (Gallup 2016; Mayer 2013) blockchain technology can reestablish trust, and contribute to more independent and active citizenship, especially—but not limited to—countries with weak institutions and unstable regimes.

However, the usage of blockchain technologies in smart cities may also lead to new challenges, for example with respect to governance. It remains an open question how blockchain technology 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 (e.g. U.S. Federal Reserve Fedcoin; McElroy 2017), BT applications in smart cities may originate from community-based P2P focused initiatives (e.g. Transactive Grid P2P energy sharing; Cardwell 2017) or from broader government or private sector initiatives (e.g. city-wide blockchain pilots from the Smart Dubai Office, Rizzo 2016; Wanxiang engagement in smart city blockchain application development, Rizzo 2017).

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 (e.g. Polkadot, Cosmos Network or Interledger). 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. For instance, annual carbon emissions of the Bitcoin blockchain are comparable to those of cities like Hamburg and Las Vegas (Stoll et al. 2019). Yet, newly developed ledger technologies–most recently IOTA with the so-called tangle–aim to mitigate these problems (Cachin and Vukolić 2017). To which extent such new technologies can be established remains to be seen.

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. For example, including blockchain-based smart city applications of established companies or further startups are potential avenues for future research. 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.

Appendix 1: Sample Structure

Smart city application area	Startups (country)			
Energy	• Bankymoon (ZA) • Dajie/Prosume (UK) • ElectricChain (AD) • Jump Software (USA) • Sunride (GER)	• Electron (USA) • Energy Blockchain Lab (CHN) • Grid Singularity (AUT) • LO3 (USA) • MyBit (CHE)	• TerraLedger/Voltmarkets (USA) Smappee (USA) • Solether (n/a) • Batan (UK) • Omega Grid (USA)	• Sonnen (USA) • SunExchange (ZA) • Wattcoin (USA) • Consensys (USA) • SolarChange (ISR)
Transportation	• Arcade City (USA) • T-Mining (BEL) • Chasyr (USA)	• Oaken Innovation (USA) • Parq (NL)	• Powertree (USA) • La'Zooz (ISR) • Slock.it (DEU)	• Cloudpark (USA) • Parkgene.io (GRC)
Building	• Ubirch (DEU) • HomeSidekick (USA) • Propy (USA) • Smappee (USA)	• Silvertown (UK) • Slock.it (DEU) • Ubitquity (USA) • Blocksquare (SVN)	• Tapclose (USA) • Flip (USA) • BrikShares (IT) • Propify/Coicio (USA)	• Cleverent (USA) • REIDAO (SGP) • REX (USA) • Realblocks (USA)
Health	• Blockpharma (FR) • BurstIQ (USA) • 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) • DAERS (CH)
Government	• Advocate (USA) • BitFury (USA) • Bitland Global (GH) • Follow My Vote (USA) • Neocapita (AUT)	• 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) • Votem (USA)

(n/a) expresses startups that do not provide a registered office

Appendix 2: Classification Results

Layer	Dimension	Sub-dimension	Characteristics								
Smart city application area	***Energy*** (24%)		P2P transaction platform (32%) [10%]	Crowdfunding platform (24%) [8%]	Corporate energy transactions (32%) [10%]	Carbon asset management (8%) [2%]	Research (4%) [1%]				
Smart city application area	***Transportation*** (12%)		Tolls (9%) [1%]	Ride sharing (27%) [4%]	Parking (36%) [5%]	PEV charging (18%) [2%]	Container logistics (9%) [1%]				
Smart city application area	***Building*** (20%)		Energy consumption (18%) [4%]	Property transactions (47%) [10%]	Funding (29%) [6%]	Building access authorization (6%) [1%]					
Smart city application area	***Health*** (18%)		Patient records (50%) [13%]	Research data provision (23%) [6%]	Pharmaceutical authenticity verification (9%) [2%]	Digital nudging (14%) [4%]	Emergency alerts (5%) [1%]				
	Government (26%)		Registry services (22%) [6%]	Voting (26%) [7%]	Citizen dialogue (17%) [5%]	Donation tracking (22%) [6%]	Digital citizenship (13%) [4%]				
Business model	*Value proposition*	***Primary block-chain benefit***	Securi-ty by design (15%) [40%]	Audita-bility (17%) [45%]	Smart contracts (18%) [50%]	Micro trans-actions (10%) [27%]	Disinter-mediation (13%) [37%]	User verifi-cation (7%) [18%]	Data reconcil-iation speed (10%) [27%]	Tokeni-zation (6%) [17%]	Anony-mity (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 compo-sition***	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.

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