The Cryptoeconomics of Cities, Data and Space

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Abstract: We explore the connection between new decentralised data infrastructure and the spatial organisation of cities. Recent advances in digital technologies for data generation, storage and coordination (e.g. blockchain-based supply chains and proof-of-location services) enables more granulated, decentralised and tradeable data about city life. We propose that this new digital infrastructure for information in cities shifts the organisation and planning of city life downwards and opens new opportunities for entrepreneurial discovery. Compared to centralised governance of smart cities, crypto-cities can be understood as more emergent orderings. This paper introduces this research agenda on the boundaries of spatial economics, the economics of cities, information economics, institutional economics and technological change.

Keywords: Blockchain, Distributed Governance, Smart City, Spontaneous Order, Blockchain Supply Chain, Data Markets, Proof-of-location

1. INTRODUCTION

The concept of a smart city is built around the insight that many of the physical aspects of a city—including the movement of people and things, or the measure of variables such as air quality or congestion, or the state of various infrastructures and utilities—can benefit from continuous flows of digital information that can be analysed and used as an input into city operations and planning. Smart city agendas emphasise the importance of data in the coordination of city operation and life, and offer the prospect of better governed, higher functioning, and more liveable cities as a result of investment in smart city technologies (Manville et al., 2014; Öberg and Graham 2016).

Smart city agendas, however, generally involve centralised collection and governance of city data. This centralised data is subsequently used as inputs into centralised planning decisions (e.g. optimising traffic flows). In this paper we examine how new decentralised digital technologies for recording and coordinating information open possibilities for more spontaneously ordered cities. Our focus is on two technologies—blockchains and other distributed ledger technologies, and proof-of-location networks—as the foundation for more decentralised data markets that are inputs into entrepreneurial solutions to problems. We argue that cities will become more spontaneously ordered through comparatively decentralised data production about city life.

While our focus is on two frontier technologies, our contributions also apply more broadly to how digital infrastructure changes the ordering of cities, including the impacts that these technologies have on the conception and implementation of smart city agendas.

We proceed as follows. Section 2 introduces blockchain technology as economic infrastructure. Section 3 introduces cities as emergent orderings, as spaces where individuals and entrepreneurs coordinate and discover information and opportunities near others. Section 4 examines the smart city agendas in this context. Section 5 explores how blockchain technology and new locational technologies facilitate better information about movement in city life. Section 6 concludes.

2. BLOCKCHAIN AS ECONOMIC INFRASTRUCTURE

First invented to create the digital currency bitcoin (see Nakamoto 2008), blockchain technology sits within a broader category of distributed ledger technologies. The innovation in blockchain technology is that it uses a unique combination of cryptography, peer-to-peer networking and economic incentives to enable networks of computers to create distributed ledgers. Blockchains industrialise trust, converting economically valuable energy into trust in the contents of a distributed decentralised ledger (Berg et al. 2020). This contrasts with the conventional centralised mechanisms of maintaining ledgers, including nation states (e.g. property titles) and hierarchical firms (e.g. banks).

In the decade since blockchains first emerged there has been a surge in innovation around how blockchains operate, including their governance (e.g. permission to update the ledger), consensus mechanisms (i.e. how the network comes to consensus) and other characteristics (e.g. privacy). While debates continue around the precise definition of a blockchain—including the boundaries of where blockchains meet other distributed ledger technologies or distributed databases—for the purposes of this paper we generically refer to these innovations as blockchains. Generally blockchains are more decentralised, robust and censorship-resistant governance structures compared to centrally maintained ledgers. Through the lens of comparative institutional economics, the entrepreneurial experimentation around blockchain today is a discovery process over which governance problems are best solved by blockchains compared to more centralised mechanisms. Current experimentations include the recording of democratic votes (see Allen, Berg, Lane, Potts 2018; Allen, Berg, Lane 2019) and new legal systems (e.g. see Werbach and Cornell 2017).

Given the importance of trade—and the movement of people more broadly—for city planning and the identification of market opportunities, in this paper we focus on the application of blockchain to supply chains. Blockchains can act as new economic infrastructure for information about goods as they move through supply chains (Allen, Berg, Davidson et al 2018; Allen, Berg, Markey-Towler 2019). Rather than information about goods (e.g. provenance, characteristics, stewardship) being recorded in ledgers maintained in siloed hierarchies—for instance, by updating internal databases—that information can be recorded in decentralised blockchain ledgers.

Blockchains do not validate that information the information that is in the ledger is true. Rather, blockchains provide the infrastructure for data to be stored in a decentralised way that is difficult to tamper with after the fact. For this reason, blockchains—particularly in the application to supply chains where information about physical goods must align with information in the ledger—have been complemented with other technologies for information inputs, such as Internet of Things (IoT) sensors. Proof-of-location networks (discussed in Section 5 below) produce location data (e.g. an alternative to centralised GPS) that relies on decentralised physical infrastructure ("beacons") that are economically incentivised to provide geospatial data of objects with corresponding sensors nearby. More detailed, trusted and tradable data about things as they move can then be recorded in blockchain ledgers, creating a new architecture for data in cities.

In this paper we ask what the implications of this deeper and decentralised information are for cities. We draw on institutional cryptoeconomics as an analytic framework (Berg et al. 2019; Allen et al. 2020), that itself draws on institutional economics. Application of institutional cryptoeconomics to this problem has several implications: (1) that new decentralised technologies including blockchains and proof-of-location networks will shift the governance of data from centralised siloed to decentralised networks; and (2) that by opening up data markets, we expect further bottom-up entrepreneurial coordination and value creation in cities, making them more emergent. This suggests a new vision for smart city agendas in which citizens and businesses can engage more fully in data markets and searching for entrepreneurial opportunities.

3. CITY AS EMERGENT ORDER

Economists have long sought to understand the economics of space, and the spatial organisation of cities as an outcome of economic forces. Cities are a complex mix of top-down and bottom-up planning. Here we examine the emergent orderings underpinning cities where people coordinate information and make plans about entrepreneurial opportunities. This understanding of cities as emergent orderings reliant on information foreshadows our predictions about how new decentralised information technologies open potential for more emergent ordering in cities.

Alfred Marshall drew a relation between agglomeration tendencies and industrial productivity, suggesting that workers became more efficient in urban centres that provide a denser, more specialised labour market, access to more specialised services and facilities, as well as access to non-excludable knowledge bases (Florida et al. 2017). The Marshallian insights were extended by Arrow (1962) and Romer (1990), who have suggested that economic actors operating within the city environment benefit from knowledge spillovers arising from firm proximity. When firms are close, workers may share ideas, which bring about product innovations that significantly contribute to economic growth. These innovations, however, may not be easily appropriated by individual firms in terms of additional profitability. A key question following from this is to what extent spillovers are observable between a concentrated set of firms within a given industry, or between firms across industries as the benefits of diversity take effect (Jacobs 1969). The extent to which "Marshallian" or "Jacobsian" externalities have taken effect in practice remains the subject of intense debate within the urban economics and innovation literatures (e.g. Glaeser et al. 1992; Beaudry and Schiffauerova 2009; Caragliu et al. 2016).

The neoclassical identification of externalities from agglomeration in cities provides a basis for the design of public policy to internalise them. Policies to address the strains and stresses of urbanisation not only take the form of generic Pigouvian taxes and subsidies in response to externalities effects, though proponents of policy intervention would suggest circumstances may not necessarily preclude such initiatives. Other policy positions include regulations to recalibrate land use and development standards, and urban planning procedures, in often prescriptive ways (Pennington 2002; Staley 2004).

The claim that the economic externalities of cities need public management has been criticised from a variety of economic vantage points. The critiques relate to whether bureaucrats and other political actors can successfully harness all the diverse economic knowledge generated within metropoles in the implementation of policy. Challenges to policy efficacy also rest upon the idea that urban areas are open and dynamic systems, and that the diverse individuals participating in city life are not presumed to maintain similar correspondences between their particularised means and ends (Cox and Gordon 2017; Kichanova 2018). Because of these complexities, urban activity cannot be reasonably compressed, or reduced, into simplified sets of production and/or utility functions that lend themselves to manipulation by city managers and other relevant policymakers.

The perennial economic problem, then and now, concerns the effective coordination of production, distribution and exchange activities. As Friedrich Hayek (1945, 521) famously conceptualised, the task of coordination in the economic context intrinsically involves the distillation of "the knowledge of the particular circumstances of time and place." He continued,

> practically every individual has some advantage over all others in that he possesses unique information of which beneficial use might be made, but which use can be made only if the decisions depending on it are left to him or are made with his active cooperation. *We need to remember only …*

> *how valuable an asset in all walks of life is knowledge of people, of local conditions, and special circumstances* (ibid., 521-522; emphasis added).

His argument also applies to cities and to the processes of urban development as the basis of, and responses to, the need for better economic coordination, as has been explored by Andersson (2005), Desrochers (1998; 2001), Gordon (2012), Ikeda (2004), and Stam and Lambooy (2012), among others. These studies have emphasised the core Hayekian insights on "the role of social institutions, the prevalence of inefficiency and discoordination, the relative importance of processes over endstates, the centrality of entrepreneurial discovery in the market process, and the nature and significance of spontaneous orders" (Ikeda 2007, 215). Whereas most, if not all, of these conceptual features are directly related to the research work of contemporary Austrian economists they are also explicated by the likes of complexity, evolutionary and network economic theorists, as well as by specialists in other disciplines such as geography (Allen 1996; Glücker 2007; Boschma and Martin 2010).

A spatially-aware Austrian school is closely associated with the dictum of creative entrepreneurship as a cornerstone for coordinative economic activity in the urban environment. "The diversity of knowledge, skills, and tastes that one finds disproportionately in the living city are potent enablers of entrepreneurial discovery. The density and resulting proximity among individuals within such places narrow the gap between the potential opportunity and its actual discovery" (Ikeda 2007, 215). According to Andersson (2005) the identification of profitable market opportunities by an entrepreneur is indelibly shaped by locational choice which, in itself, serves as an entrepreneurial act. Specifically, entrepreneurial actors may perform a mental calculus that arbitrages between choice of locations (including remaining in the present location) in the hope of attaining future profits. It is recognised, however, that the conduct of locational entrepreneurship is not conducted perfectly (Banczyk et al. 2018) and nor are locational decisions necessarily dominated by economic considerations under all circumstances (for example, cultural concerns may be important; see Palmberg 2013).

The growth potential associated with agglomeration economies, at a micro- or meso-economic level, are shaped by network relations established by heterogeneous individuals working and residing in relatively close proximity to one another. Face-to-face meetings enable people to share perspectives, establish trustful relations and coordinate to launch new economic ventures (Cox and Gordon 2017), and new communications technologies facilitate connections to absorb information and knowledge. Palmberg (2013) also refers to the role of clubs and associations in facilitating knowledge diffusion. These mechanisms of inter-personal connection are, more or less, subject to "network effects," which become more apparent in relatively densely populated environments such as metropolitan centres and large regional towns. Although such activities are not costless, it appears that the costs of exclusion from entrepreneurially-related network opportunities by virtue of residing outside of cities are significant (e.g. Saxenian 1990).

Several property, relative prices, contracting and a monetary system are fundamental coordinative institutions. According to Ikeda (2007) these institutions should arise, largely in spontaneous fashion, within city environments that necessitated the ability of numerous traders to strike mutually agreeable exchanges of goods and services at reasonable prices. Given the bountiful opportunities to shirk effort, renege on bargains and to exercise opportunism more broadly, the development of abstract and generic institutions serving as "rules of the market game" are seen as necessary to harness inter-subjective comprehension, forge shared expectations and, importantly, develop a sense of trust between strangers in complex economic contexts. Indeed, we can compare different institutions on how they coordinate information—taking the perspective of "epistemic institutionalism" (see Hayek 1945, Boettke 2018). The phenomenon of the "fundamental institutions for market-tested betterments" may even more clearly coincide with the historical emergence of certain localities as regional and global trading hubs, as described by Clark (2016). This is not to suggest that economic institutions did not emerge in rural and other non-urban localities, but that the potential for developing such institutions would be most pressing in the city.

The physical and functional forms of a city reflect a spontaneous order which is "the result of human action but not of human design" rather than the product of singular or overarching planning and design by any given individual economic, social or political actor. The notion of spontaneous order, or at least ordering which assume a largely emergent character, has a long tradition in political economy. Jane Jacobs (1961; 1969) remains arguably the leading exponent of the "emergent urbanism" view that metropolitan locations do not arise as the consequence of the imposition of the grand schemes of architecture and land planning upon countless numbers of people. Indeed, the excitement and life given to the city by its diverse, even in parts eccentric, inhabitants release the immense economic energies of urbanisation, even if no one person in particular intended for agglomeration-related growth and living standards improvements to materialise. The variable, multiple-ended strivings from the street-level up makes up the observed dynamic episodes of growth and development in the aggregate, even if non-intentional on the part of any given individuals, is at the heart of the city as a spontaneous or emergent order.

The emergent ordering of the metropolitan environment contains many elements of decentralised planning. Individual entrepreneurs make plans supported by urban knowledge spillovers and network logics. There are also evident examples of urban landscapes and functions that result from deliberate planning associated with collective action. A local governmental authority may construct a park in the centre of town, however the patronage of the park and the uses to which the park are put are not consciously designed and implemented by any single person. As mentioned by Ikeda (2007, 215),

> [t]he layout of public transport, utilities, and other aspects of the physical infrastructure of a city is the result of careful, conscious planning, but the entrepreneurially driven competition that emerges from it, that which gives life to the living city, is not.

Thus, the multidimensional uses of urban assets and considerations of amenity reflect the "multifaceted spontaneous networks that consist of individuals who cover many different fields of knowledge, interests, and activities" (Palmberg 2013, 21). From this perspective we can see that cities are complex mises of bottom-up and top-down plans. In the following section we turn to how frontier technologies shift smart city agendas. We describe the evolution from "smart cities"—central planning based on centralised data—to "crypto cities"—bottom-up entrepreneurial search based on decentralised data markets.

4. FROM SMART CITIES TO CRYPTO CITIES

The functionality and even liveability of cities and large towns are threatened by an array of economic, social, technological and other challenges, including easing transport congestion, maintaining personal and economic security, preserving environmental amenity, and improving access to local public services. How can we best coordinate resources, and maintain and even enhance their value, in highly contingent and uncertain environments?

Smart cities grew out of the 1990s concept of New Urbanism, which sought to redesign the built environment to capture environmental, social and similar values. The concept of smart city also has roots in the notion of "intelligent cities" as physical environments in which information and communication technology and sensor systems are embedded into physical objects and urban settings (Steventon and Wright 2010; Caragliu et al. 2009; Hollands 2008). In intelligent cities, information and communication technologies substitute many of the coordination and control roles of hierarchy, motivating new organization forms that focus on process instead of function (Setia and Patel 2013).

Proponents of infusing smart city thinking into organisational practices and public policies refer to a gap between the availability of data and the capacity of firms and governments to apply the data to bring about more efficient deployment of resources that, in turn, resolve city-wide problems. As Goldenfein et al. (2017, 1) argue:

> The key insight of the smart city movement was that a city generates terabytes of data in the course of ordinary interactions among people, among things, and between people and things, but that very little of it is captured and used. The smart city is an approach to public infrastructure and urban governance that seeks to capture and use that data in real time to improve the effectiveness of the city's operations. The implication is that by developing 'smart infrastructure' that can sense the activities around it, better and more efficient use of urban resources becomes possible.

The application of technological innovation to make cities work more efficiently by harvesting and interpreting mountains of city-gener`ated data is at the crux of the smart city agenda. Remote sensing and similar technologies used to track location, such as "radio-frequency identification" (RFID) scanners and barcoded objects, are coupled with the web-connected sensing devices (so-called Internet of Things) to allow objects to connect, interact and exchange data.

Blockchain is a further potential addition to this technology stack to maintain real-time data intelligence to support infrastructure connectivity (Scott 2016). Given that further quantification of urban economic activities will be accompanied by growth in data collected and exploited, the attributes of blockchain in promoting the integrity and provenance of data and digital assets is complementary to the smart city agenda (Wellers et al. 2017). Demand for digital privacy by consumers or citizens, or demand to conserve the integrity and security of their information into the future, can be supplied by blockchain protocols that enable individuals to manage their own data flows as they see fit (see Berg 2018).

The smart city agenda also seeks to apply big data analytics including machine learning to capture and organise large amounts of disparate and unstructured data to uncover correlations, patterns and other useful information (Rouse 2012). In particular, the big data that interests firms are what is called "found data"—that is, the digital exhaust of Web searches, credit-card payments and cell phones (Harford 2014). Part of the perceived improvements that big data could bring forth is to break down the lack of interoperability, and the concomitant duplications and incompatibilities, associated with proprietary data silos managed by individual firms, government agencies and other organisations based in cities (Pettit et al. 2018).

Whilst the big data analytical project has attracted significant attention in academic, business, media and political circles, its merits as an underlying driver for refashioning economic and other interactions within cities have been questioned in some circles. Large quantities of data does not, in itself, necessarily provide meaning for those tasked with interpreting the information received, and that data could yield spurious correlations and other problems that could lead to potentially disastrous outcomes for urban functionality if carried through automatically to policy. In essence, the emergence of big data capabilities does not obviate from the requirement that "data … needs to be robust, accessible and interpretable if it is to provide cities and companies with meaningful opportunities and solutions" (Öberg and Graham 2016, 531).

The smart city agenda is built on a centralised vision of city information architecture. This agenda may well be rationalised as a means to drive substantial improvement, but implicitly it holds the governance surrounding decision-making in the city invariant: "the comparative economic organization of the city remains unchanged. The same things are still done by the same people with the same division of task; it just gets done more efficiently" (Goldenfein et al. 2017, 3). The critique of the smart city as a model of large scale but *centralized* and *closed* computation closely relates to the Hayekian critique that large-scale ventures, such as reframing the dynamic life of cities on "smart" principles, often lack appropriate knowledge (that is, information in its rightful context) for successful implementation. The centralised (re)planning of the city, in this view, cannot overcome the knowledge problems accompanying the planners' distance from those "persons on the spot" maintaining partial but, still, economically valuable knowledge that all combine to create the know-how that makes the large, modern city into economic powerhouses.

The smart city agenda in theory represents an attempt to forge greater partnerships between disparate actors within the urban economy through the mass integration of data and information generated by city-based activities. However, it is predicated that "on a city level the traditional monocentric governance is still a dominant approach, with most people taking for granted that services like building urban infrastructure, maintaining public spaces, enforcing land use regulations, and managing externalities are better delivered by state agencies" (Kichanova 2018, 3). Stated differently, what is often overlooked is the fact that the "kludgeocracy" (see Teles 2013) of existing organisational forms within the city itself presents a barrier to the full release of creative and dynamic forces which are central to an appreciation of the city as an *emergent, not constructivist*, order.

The high-modernist construct of large corporations and government agencies, each dominating the city econo-scape, has been intimately associated in an historical context with the evolution trend of data management toward highly centralised, siloed ledgers. There is no doubting the immense economies of scale and production values that modern economic organisations have already generated, courtesy of their authoritative roles of recording, storing and validating data (MacDonald et al. 2016), but the onset of blockchain technology has only recently kindled an awareness of the foregone economic opportunities associated with the past lack of distributed yet secure ledger technologies. As Posner and Weyl (2018) observe, the emergence of data as lucratively valuable assets in their own right has given new meaning to the sense of self-preservation pressingly felt by those entities already presiding over large, but centralised and non-interoperable, datasets. The additional downsides of acting on such motives of self-preservation by already-existing data hoarders are the continuation of rents, inequalities, and power concentrations which create non-trivial harms for many city residents.

A smart city may therefore require *different* institutions, more decentralised institutions, in order to harness and make better use of decentralised data. Blockchain and associated technological innovations may be the institutional infrastructure that is necessary to "significantly shift the optimal arrangement of economic organizations and institutions in modern cities" (Goldenfein et al. 2017, 2). Integrating blockchain and related technologies with an appreciation of the urban environment as an emergent order moves us from the smart city to the crypto-city.

Crypto-cities are enabled through new decentralised technologies. Blockchains can act as the foundational infrastructure for the decentralised storage and coordination of data and associated transactions and contracting. This decentralised data enables governance of economic relations in a decentralised manner. The decentralised nature of data stored on blockchains—including that information about supply chains—suggests that a crypto-city may possess distinguishing features compared to more centralised smart city agendas. As opposed to the top-down smart city agenda, a proposed crypto city agenda enables the coordinative and governance opportunities wrought by technology to be appropriated by entrepreneurs seeking to discover new avenues for gain (in a mutually beneficial way with others) in city-spatial locations.

5. DECENTRALISED INFORMATION AND THE CRYPTO-CITY

Better visibility along supply chains could create publicly accessible pools of data about human interactions within urban areas, leading to further scope for entrepreneurial discovery. Given the impacts of trade upon the growth and change of urban spatial environments— including logistics networks, planning, transportation, environmental amenity, provenance, and so on—our understanding of blockchain-enabled trade infrastructure provides a fruitful avenue for research. For instance, what are the implications of blockchain-based supply chain infrastructure for existing modes of urban planning and development? Does this understanding have any consequences for smart city agendas? How, and to what extent, could high-trust supply chains improve the possibility of developing "free trade zones"? How can the information that is collected—for instance, about where and how goods move through a city—be used to discover entrepreneurial opportunities solving urban problems? Can artificial intelligence be used to mine these pools of city information?

We can distinguish between two main types of supply chain management flow: material or information. Smart cities will impact differently on each type of flow. Given the needs for storage capacity and processing power about city data, there will be opportunities for companies that are located in the middle of large amounts of data flows (e.g. information about products, buyers, suppliers, consumers, etc) and are capable of aggregating and analyzing them (Manyika et al. 2011). Firms can therefore that data to centralize decisions more efficiently. Smart cities and big data may stimulate more centralization of information flows.

Supply network complexity may positively impact the ability to access and share information across the supply chain because more actors are involved in exchanges within the network (Caridi et al. 2010). Thus, big data applications (e.g. open data) can benefit from the input generated by a higher diversity of actors in a structurally complex network. However, Skilton and Robinson (2009) argue that tight coupling among firms is more difficult to achieve in complex supply networks, so failures in information exchange may be a problem. The implementation of big data in supply chain management activities does not necessarily imply more efficiency (Miller and Mork 2013). Indeed, smart cities and big data tend to increase structural complexity because they amplify the amount of information necessary to monitor the state of the system. Unless firms completely redesign their distribution networks, an increased structural complexity could increase costs and decrease flexibility. In addition, the complexity of interactions between so many heterogeneous automated systems may generate more mobility problems than solutions. The conventional focus of Smart City agenda is upon top-down rearrangements to urban forms: congestion taxes; banning vehicle traffic; rezoning. The issue is whether existing fiscal and regulatory models to improve supply chain functionality in cities will elicit additional creative discoveries and innovation.

Trade platforms and supply chains are shaping up as the major use case for blockchain technology. Blockchain technology can solve a major and growing problem with the global trading order—namely the problem of coordinating trusted information between supply chain participants. Every time a good or service moves, information moves with it. The quantity of information associated with each product continues to grow, and the costs of dealing with this information, from compliance, auditing, verification—trust, in a word—is becoming a greater and greater share of the costs of the global trading system. Blockchain and other information technologies are now being applied to economise on the information costs underpinning supply chains. For instance, in 2017 IBM and Danish shipping company Maersk announced their TradeLens blockchain solution to facilitate "the real time exchange of original supply chain events and documents" (IBM 2017). Walmart has since announced their intention to use the IBM Food Trust platform to facilitate the sharing of provenance information by their leafy green suppliers in the wake of an E. coli outbreak (Walmart 2018). Relevant information could include ownership data, time stamping, location data and other product specific data (e.g. see Abeyratne and Monfared 2016). This information helps establish provenance and thereby potentially identifies counterfeit goods (Hackius and Petersen 2017; Kim and Laskowski 2018).

New digital supply chain infrastructure must satisfy the demands for trusted information about the provenance of goods by stakeholders including consumers, producers and governments. As transportation costs and political costs fall, the portion of total trade costs that are information costs rise (see Allen, Berg, Davidson et al. 2019). Further, given that information costs also increase with the complexity, length and volume of trade on supply chains, it is unsurprising that information costs of global trade are likely rising as a proportion of total trade costs. The information flows of international trade are still often organised as transfers between separate organisations, despite efforts to digitise supply chain information. Each firm in a global supply chain passes off information until it can be passed to the next actor on the supply chain, and adding to that information as the nature of the good changes. Moving goods and their information along a supply chain can be remarkably complex, requiring hundreds of different actors, including exporters, importers, logistics companies, shippers, retailers and governments.

As supply chains become longer and more complex, information changes hands more often and across more relationships, potentially leading information loss or fraud. The production and maintenance of trusted information about goods, however, is not costless. Individuals create organisational structures—including hierarchial integration within firms—as mechanisms to produce supply chain information, ensure its integrity, and communicate that information between relevant parties. For instance, some supply chain information is produced through brand reputation, "repeat transactions … and social norms that are embedded in particular geographic locations or social groups" (Gereffi et al. 2005, 81). Siloed hierarchies along a supply chain communicate information—for example through paper-based bills of lading—between each other to maintain and update ledgers of information. Estimates to the administrative cost of this paperwork varies from 15 per cent of the value of goods shipped (Groenfeldt 2017) to being equal to the cost of physically moving those goods (Popper and Lohr 2017).

While the internet has enabled greater efficiency in some housing related processes—such as online real estate and mortgage advertising and online transactions—it has not fundamentally changed the ledger of transactions or its management. The internet protocol is not equipped to transfer value in a trusted fashion. As a result, bureaucracies, banks, lawyers and estate agents are still required to perform the institutional arrangements that make property ownership possible, including the enforcement of transactions, the granting of exclusive use, as well as transferability and inheritability. Data is managed in central repositories and protected against security breaches at significant public expense.

The blockchain economy is fundamentally different from the digital economy we have known to date. While the Web 2.0 economy has been characterised by centralising forces, resulting in large companies that handle transactions on our behalf, the cryptoeconomy theoretically does not require the same market or government mechanisms for trusted transactions to be achieved, potentially doing away with current processes of licensing, self-regulation and branding. Instead, peer-to-peer transactions, as well as direct, transparent incentives for participation, are the foundations of the blockchain economy. In economic theory, complex evolving systems typically move from centralised to decentralised systems (Coase 1960); centralisation enables enforcement and creates knowledge system rules but can also come with costs (corruption, inflation, security costs).

There are various degrees of decentralisation across blockchains and other distributed ledger protocols. Many blockchain-enabled supply chain projects are based on 'permissioned' architecture (e.g. HyperLedger Fabric) where the ability for participants to read and write to the ledger is controlled. These applications contrast with more open 'permissionless' protocols where anyone can read and write to the ledger. While permissioned ledgers are more centralised than permissionless blockchains (although more decentralised than conventional hierarchical data management), they have been adopted partly because they provide greater data privacy and bespoke data access rights and do not require a cryptocurrency to align economic incentives. Data rights, in particularly, are major considerations for supply chain participants (see UCL CBT 2019).

Blockchain-based supply chain infrastructure means consumers might not only be able to access cheaper and more trustworthy information about the goods that they buy, but also more granulated and detailed information on previously unobservable characteristics (Allen, Berg and Markey-Towler 2019). That is, information about the vectors of goods that were either not previously produced or not previously observable due to transaction costs might become possible. There are several implications of blockchain-based supply chain infrastructure on the operation of market prices. First, we anticipate a *de-commoditization of goods*. Two products previously considered identical because of a lack of information about their differing vectors of characteristics might now be reliably differentiated into two different markets. The second order effect of this is more granulated prices. That is, a *disaggregation of prices*, perhaps splitting existing markets into new markets of premium and non-premium segments. The precise margins at which additional trustworthy information will shift the price of goods will emerge over time, and will be directly related both to the subjective perceptions of consumers buying those goods, and the entrepreneurial efforts of people seeking to create the blockchain-based infrastructure that will produce and govern that information. Finally, to the extent that market prices represent the aggregation of distributed and contextual information of market participants (Hayek 1945), we would expect over the longer-term *more effective market coordination*. That is, market participants will be better able to observe and put to use Hayekian information to achieve their objectives.

Blockchains are unable to autonomously interact with real-world individuals or events and hence rely on 'oracles' to transmit data about temperature, contractual performance and so on (De Filippi and Wright

2018). These oracles can also enable dynamic adjustment of shipping routes and prioritisation based on the attributes of the goods shipped, a products 'health' for instance. Smart contracts in supply chain could perform many functions, including transferring the ownership of goods as they move between actors, and executing payments when items are delivered.

Blockchain-based supply chains may also leverage more complex technologies to input information via sensors (Kim and Laskowski 2018). One example of this is the development of 'smart containers' based on the Internet of Things (IoT) where a number of sensors record information—such as temperature and GPS data—that is then uploaded to a blockchain-based distributed ledger. Such technologies are important to deal with the 'garbage-in-garbage-forever' problem facing blockchains—that blockchains themselves do not validate whether the information in a blockchain is true, rather they provide confidence that data has not been altered once it was digitally signed. The adoption of IoT and related technologies are a shift away from human-centred data input towards technology-centred data input, reducing some of the challenges of fraudulent blockchain data.

Another potential technology that inputs information into blockchain ledgers are "proof-of-location" protocols. Proof-of-location protocols provide for robust geographic information about users or things without relying on a central authority to verify that information (Brambilla et al. 2016). This includes protocols such as FOAM, where a physical infrastructure is built that detects and uploads information about location to a blockchain-based system (Kohut 2018). That information may also be leveraged to execute smart contracts between supply chain parties.

Trusted location data is an economically valuable product and service. Proof of location provides an input into economic production across supply chains and logistics, energy systems, transport systems and mobility, real estate, finance, and many other sectors, by verifying that some event or process has occurred at a particular location. This can trigger a payment, a privilege (i.e. being able to view sensitive documents only within a specific location), layers of privilege, or a further phase in a contract. In turn, the ability to spoof location can be used for opportunistic or even fraudulent purposes. Location spoofing is in this sense the same as the double spending problem with digital money. The goal of proof-of-location using blockchain technology is to provide consensus about whether an event or agent is verifiably at a certain point in space and time.

Trusted location information allows digital systems to connect to the real world. The problem with current centralised location ecosystem, mostly built around satellites, is that it is siloed, unreliable, and insecure. Blockchains enable decentralised rather than centralised (satellite-based) proof-of-location. The way in which a proof-of-location process works on a permissionless blockchain can be summarised as follows:

1) Demand for Witnessing as a service. Alice wants Bob to witness location. Bob uses protocol and witnessing tool. Alice pays Bob in crypto.
2) Witnessing tool (owned by Bob) writes encrypted information about Alice's location to (permissionless) blockchain. Bob is the miner of Alice's information.
3) Alice can then share her proof of location with Carol, by pointing Carol to the blockchain.
4) As more "Bob's" (a.k.a. miners) join as witnesses, the strength of Alice's claim of proof of location becomes stronger.

Proof-of-location protocols provide data (or oracle) services to prove in a digital world where things (such as people, commodities, assets, tags, chips, contracts, etc) are in the physical world. Proof-of-location are therefore a type of *data market*. Alice needs to prove that something is at a location. Alice pays a miner to validate that information by witnessing her presence claim. Proof-of-location protocols enable individuals to own their own data about location, and create that information by paying others to witness their location. Alice can then control her information, retaining privacy. This facilitates a new architecture of property rights in data, facilitating private ownership (and possibility of trade) of personal location information. This further affords privacy control over sharing one's personal spatial information. This also creates a new way to earn income by witnessing events. These are gateway owners, and miners (Bob). Proof-of-location services and infrastructure therefore inverts current geospatial data markets, by decentralising them, rather than having data centralised through a satellite. Together with blockchain technology for the recording of information, proof-of-location protocols are a fundamental infrastructure in a decentralised crypto-city.

6. CONCLUSION

Modern spatial economics uses planning models of optimal organisation of activities in space. It mostly fails to account, however, for the economics of distributed data and information as inputs into economic value creation and spatial coordination. A new wave of decentralised digital technologies—including blockchains and proof-of-location networks—promise decentralised production and data. This suggests new more open, granulated and trusted data about city life, with broad implications for the governance of cities. Better data for decentralised decision making has the potential to solve many of the problems that spatial planning is trying to solve by creating data economies using blockchain as new data infrastructures for coordinating activity in space.

While smart city agendas introduced data, that data was managed and acted upon through centralised planning by authorities. In this paper we have described the shift from the centralised smart city to the decentralised crypto-city, enabled through new decentralised technologies. This insight has important implications for spontaneous urban planning. Blockchain technology coupled with proof-of-location infrastructure facilitates the rise of spatial data markets to facilitate self-organising economic activity in a digital urban economy. This insight suggests the need necessary to centrally plan the city, but rather to plan and design the protocols that facilitate data generation and markets. Blockchain technology provides new economic infrastructure for a property rights based and institutional rule governed economy.

This consideration of the consequences of blockchain for urban development and governance, coupled with the implications for the emergence of location service-based data markets, represents an advance on the available literatures on trade and urban economics. In this way we can see blockchain as not only inducing greater efficiencies in supply chains, but also soliciting emergence of data markets and reinforcing the city as an arena for entrepreneurial discoveries and the orderings that emerge from them.

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