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Coordination in the age of Industry 4.0: The case of blockchain

Summary: The topic of coordination arises whenever various tasks or resources must be employed together to produce desirable outcomes. Whereas the complexity of tasks and interactions needed to produce results increase coordination needs, advances in information and communication technologies (ICT) dramatically improve its possibilities. Vertically and horizontally integrated Industry 4.0 manufacturing systems, using ICT to interact with and expand the capabilities of the physical systems, both demand enhanced coordination within and between organizations, and are themselves designed to foster coordination, making coordination in the age of Industry 4.0 a particularly timely and challenging research topic. The paper contributes to the emerging stream of literature on coordination in the age of Industry 4.0 by analyzing the characteristics of blockchain as a coordination mechanism and its application to the hybrid cyber-physical production systems.

Keywords: blockchain, coordination, coordination mechanism, fourth industrial revolution, Industry 4.0

Koordynacja w dobie Przemysłu 4.0: przypadek blockchain

Streszczenie: Celem artykułu jest pokazanie blockchain jako nowego i potencjalnie potężnego mechanizmu koordynacji, uwzględniającego możliwości i wymagania systemów produkcyjnych Przemysłu 4.0. Od 2017 r. technologia blockchain przyciąga coraz większą uwagę naukowców i praktyków gospodarczych. Jednak nadal kojarzona jest głównie z rynkiem kryptowalut, co powoduje, że jej potencjał w zakresie zarządzania i organizacji przedsiębiorstw nie jest wykorzystany.

Słowa kluczowe: blockchain, koordynacja, mechanizm koordynacji, czwarta rewolucja przemysłowa, przemysł 4.0

JEL D23, D24, D86, L14, L15, L17, L23

Coordination is a perennial topic in management studies. It arises whenever various tasks or resources must be employed together to produce desirable results (Malone and Crowston, 1990). The advent of Industry 4.0, predicated on the growing interconnectedness and interdependence of technologies and business organizations (Kagermann, Wahlster and Helbig, 2013) and demanding intense interactions and cooperation to speed up innovation, cross-fertilize transformative digital technologies and advanced physical technologies and to shorten time to market, make the topic of coordination more relevant than ever.

Early studies on coordination focused on organization of tasks and resources within firms (e.g. Van de Ven, Delbecq and Koenig, 1976), but with the passage of time interorganizational perspective started to prevail, following academic interest in other strategic interactions, namely cooperation and competition, which studies on coordination can complement and enrich. Rapid progress of information and communication technologies dramatically increased coordination possibilities, which in turn opened up new strategic and organizational choices including ecosystems, platforms and multisided markets, value nets, etc., complementing more traditional options of supply chains and value chains, networks and alliances, among others (Adner, 2017, p. 50-53). Industry 4.0 manufacturing systems, built on the recent advances in digital technologies (e.g. Big Data, cloud computing, predictive analytics, machine learning) and advances in physical manufacturing technologies (e.g. 3D printing, nanotechnologies), form hybrid structures set to face challenges of manufacturing in the digitalizing world. Such systems, fusing digital and physical worlds (Schwab, 2016), embrace novel interdependencies and face unprecedented coordination challenges within and between organizations, creating a fertile ground for a new wave of studies on coordination.

However, the coordination problem in the Industry 4.0 setting is only beginning to attract due interest (c.f. Pietrewicz, 2019b). The aim of this paper is to contribute to advancing such research by presenting blockchain as a novel and potentially powerful coordination mechanism addressing the possibilities and demands of Industry 4.0 production systems and inferring its relative advantages for the Industry 4.0 manufacturing value chains. Since 2017, blockchain technology has attracted increased academic and popular attention, however its dominant association with cryptocurrencies has inhibited understanding its potential in management and organization of enterprises. The current study seeks to contribute to bringing blockchain into line by emphasizing one of its important and little studied aspects.

The remaining of the article is structured into four sections. The first one briefly introduces the notion of coordination, the second outlines the characteristics of Industry 4.0 with a special emphasis on coordination, the third section depicts coordination with blockchains and specific applications of the technology in the realm of Industry 4.0 manufacturing systems, and the final section concludes.

The problem of coordination

Although the term “coordination” is intuitively understood and widely used, its precise definition causes difficulties. According to the online Cambridge Business English Dictionary, coordination is *the process of organizing the different activities of people involved in something so that they work together effectively*. In management literature, coordination has been defined as the organization of individuals’ efforts toward achieving common and explicitly recognized goals (Blau and Scott, 1962), the act of working together harmoniously (Malone and Crowston, 1990, p. 4), the integration or linking together of different parts of an organization to accomplish a collective set of tasks (Van de Ven, Delbecq and Koenig, 1976), bringing into a relationship otherwise separate activities or events, typically with the goal of increasing efficiency (Frances, Levacić, Mitchell and Thompson, 1991, p. 3), and managing dependencies among activities (Malone and Crowston, 2012, p. 11), which result from orientation at a common goal (Malone and Crowston, 1990, p. 4).

Coordination can be defined as either the process of coordinating or the outcome, i.e. the state in which activities are coordinated. It can be achieved using multiple coordination mechanisms, categorized as explicit (task programming and communicating) and implicit (cognition based on shared knowledge) (Espinosa, Lerch and Kraut, 2004), organization mechanisms and communication (March and Simon, 1958), standardization of tasks, plans, mutual adjustment (Thompson, 1967), direct supervision, mutual adjustment and standardization (Mintzberg, 1979), and price, non-price, and flow coordination mechanisms (Fugate, Sahin and Mentzer, 2006). A selection of coordination mechanism categorizations is presented in Table 1.

The importance of coordination studies for management scholars reflects its role in managing strategic interactions (Hardin, 1990) and in the achievement of firm objectives (Espinosa, Lerch and Kraut, 2004). Coordination involves costs on the one hand, and agreement on common goals, on the other, promising to reduce inefficiencies resulting from the lack of coordination. Therefore, the choice of coordination mechanisms and its effectiveness in coordinating various value-adding activities can be a source of competitive advantage for the focal firm as well as the entire value chain and, more broadly, value system.

Advances in ICT have long been known to reduce coordination costs (Malone, Yates and Benjamin, 1987) Moreover, by shifting constraints on certain types of communication and coordination (Malone and Crowston, 2012, p. 9), ICT have opened up new strategic and organizational possibilities (Adner, 2017). Thus, the advent of Industry 4.0 can be expected to introduce new dynamics as the new age demands tackling the disparate logics of coordinating manufacturing value chains and digital ecosystems. Entirely new ways of organizing human

Table 1. **Selected coordination mechanism categorizations**

Framework's author(s)	Coordination mechanisms
Thompson, 1967	• Standardization of tasks • Plan • Mutual adjustment
Van de Ven, Delbecq and Koenig, 1976	• Impersonal (plans and rules) • Personal (vertical supervision) • Group (formal and informal meetings)
Mintzberg, 1979	• Mutual adjustment, • Direct supervision • Standardization (of work processes, outputs, norms and skills)
Malone and Crowston, 1990	• Goal decomposition (ordering activities, moving information from one activity to the next) • Allocation of resources • Synchronization of activities
Crowston, 1994	• Resource assignment • Negotiation or picking one task to do • Scheduling or acquiring more resources • Managing flow of resources
Espinosa, Lerch and Kraut, 2004	• Explicit (e.g. strategy) • Implicit (e.g. shared mental model, task awareness)
Fugate, Sahin and Mentzer, 2006	• Price • Non-price • Flow coordination
Malone and Crowston, 2012	• "First come, first serve", priority order, budgets, managerial decision, market-like bidding • Notification, sequencing, tracking • Standardization, participatory design • Scheduling, synchronization • Goal selection, task decomposition

Source: own elaboration based on respective publications.

activities may therefore become desirable (Malone and Crowston, 2012, p. 9).

Industry 4.0 and the role of algorithmic coordination

Despite the popularity of the terms "Industry 4.0" and "the fourth industrial revolution," used interchangeably, there is no agreement on the definition or the scope of the phenomenon. First of all, there are some differences in emphasis between different national versions of the Industry 4.0 concept, most explicitly between German approach emphasizing automatization and replacing humans with robots, and Japanese version stressing the role of humans in continuous improvement of processes. The present paper adopts the German version as the use of blockchain in algorithmic governance best fits into this vision.

Working definitions of Industry 4.0 comprise a variety of technologies, applications, and processes. For example, for McKinsey (2016), Industry 4.0 is driven by four clusters of disruptive technologies: (1) data, computational power, and connectivity, (2) analytics and intelligence, (3) human-machine interaction (4) digital-to-physical conversion. Reeves, Ueda and Chittaro (2017) point at 9 technology trends as the building blocks of Industry 4.0: big data and analytics, autonomous robots, simulation, horizontal and vertical system integration, the industrial internet of things, cybersecurity, cloud computing, additive manufacturing, and augmented reality. The report by Kagermann et al. (2013), currently the most cited Industry 4.0 reference, identifies and describes three integration features (horizontal integration, vertical integration, and end-to-end digital integration) and eight priority areas: standardization and reference architecture, managing complex systems, comprehensive broadband infrastructure, safety and security, work organization and design, training and continuing professional development, regulatory framework, and resource productivity and efficiency.

A systematic literature review conducted by Liao, Deschamps, Lourdes and Ramos (2017, p. 3618) has revealed cyber-physical systems (CPS), smart factories and internet of things as the main enabling features of Industry 4.0. CPS are a new generation of industrial automation systems with integrated computational and physical capabilities (e.g. Lee, Bagheri and Kao, 2015). Although advances in digital technologies typically attract most attention (Baheti and Gill 2011), Poovendran (2010) emphasizes that in order to produce a new class of production systems advances in the physical world and coordination between the two are also needed. Smart factories comprise manufacturing systems which are vertically networked with business processes within factories and enterprises and horizontally connected to dispersed value networks that can be managed in real time (Kagermann et al., 2013). Industrial Internet of Things, comprising connected machines and devices, makes it possible to create networks covering the entire manufacturing process in smart factories.

In the age of Industry 4.0, digital technologies extend, complement and optimize physical operations (Desmet, Maerkedahl and Shi, 2017) using "new intelligence external to humans", housed in "algorithms and machines" (Arthur, 2017). The world is now generating unprecedented amounts of data (Jacobson, 2013), collected by interconnected devices (Internet of Things – IoT), ranging from web browsers to smartphones to payment systems to ubiquitous sensors, which feed intelligent algorithms programmed to do "what we thought only humans could do—association" (Arthur, 2017). The capacity of algorithms to make appropriate associations (i.e. to recognize situations) and to act appropriately without the need of human interference can be viewed as the defining characteristic of the present condition. Mining huge amounts of data ("Big Data") is greatly enhancing the power of analytics, enabling dramatically higher levels of automation of processes, decisions (Bughin, Catlin, Hirt and Willmott, 2018), and, ultimately, of coordination.

Automation of processes and decisions enables the paradigm shift consisting in integration of ICT systems across manufacturing stages and hierarchical levels along entire value chains with the goal of delivering an end-to-end solution (Kagermann et al., 2013). Automaton of coordination, i.e. algorithmic coordination, allows to regulate relations between components of the system with rules encoded in computer algorithms. The main idea behind implementing such systems is that collecting huge amounts of data can be used to coordinate Industry 4.0 manufacturing systems more efficiently.

With such developments we are entering an algorithmic age where mathematics and computer science are coming together to influence, shape and guide our behavior (Danaher et al, 2017, p. 1). As sophistication of algorithms grows, they can recognize and handle more and more complex situations, to the point of autonomy, letting more and more coordination situations to be handled without the need for human engagement, freeing them from the risk of human error and, even more importantly, the necessity to exert trust to the other party of an interaction (who might choose to cheat,) or to a (trusted) intermediary. Algorithmic coordination, firstly, automates the interactions by establishing "objective" sets of rules encoded into a computer program, and secondly, it shifts its logic form "code is law", whereby technology is used to enforce existing rules, to "law is code", where technology is used to supplant old rules with new and – intendedly – better ones (Hassan and De Filippi, 2017). Thus, algorithmic coordination mechanism can effectively revolutionize coordination processes, making technology central to achieving the outcome (state) of coordination, with a positive impact on performance.

Coordinating with blockchains

Effective algorithmic coordination hinges upon trust in the quality of the algorithm and the data with which it is fed. Blockchain technology, which has been famously called a "trust machine" (The Economist, 2015), can play a key role in both of these aspects.

The concept of blockchain was first introduced in a 2008 white paper – published by pseudonymous Satoshi Nakamoto – to underpin Bitcoin – the world's first cryptocurrency and electronic peer-to-peer transaction system independent of states and intermediaries. At the basic technical level blockchain is a distributed digital ledger, that is an accounting technology of record keeping in a database (Davidson, De Filippi and Potts, 2016, p. 5-6). A ledger is a way of producing consensus about the facts that are necessary for transacting anything of value, be it products, securities or data. A major selling point of blockchains is that they produce consensus about "states of the world" in a decentralized manner and store information in a distributed network of computers (blockchain nodes), thus eliminating the need for and dependency on "trusted" intermediaries who would guarantee transactions, and virtually eliminating the risk of tampering with once recorded data.

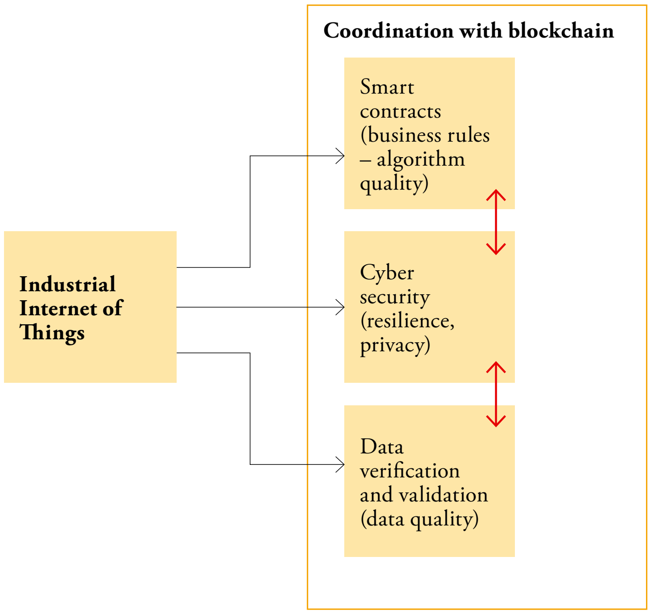
The revolutionary nature of blockchain consists in that it shifts trust from institutions towards algorithms (Lavazova, Dehling and Sunyaev, 2019). For the technology to fulfill its potential, users must trust that value-related records, once entered, are safe, that is, that the required value is either transferred or safely stored, according to the wish of the owner, and that the resultant state of the ledger is recognized by the "external world", including the other party to the transaction, that is, there is consensus about facts recorded on a blockchain. In doing so, blockchain removes the need for powerful central third-party validation and enforcement mechanisms (Davidson et al. 2016, p. 9).

Consensus about facts is instrumental to economic coordination (Davidson et al. 2016, p. 3). The capacity of the blockchain technology to manufacture it in a novel way in itself makes it a new mechanism of coordination. Blockchain, however, is more than a trustworthy ledger. Namely, it can implement business rules in the form of so-called smart contracts. Smart contract is a code-based ("pre-programmed") contract stored on a blockchain which executes autonomously (i.e. without the need for active human engagement) whenever conditions stipulated in the code are met. While contracts in themselves are coordination mechanisms (Schepker et al., 2014), the characteristics of smart contracts add an extra layer and contribute to making blockchain a composite rule-based coordination mechanism (Pietrewicz, 2019a).

While all four categories of smart contracts described by Grasso (2018) – distributed applications, smart legal contracts, Decentralized Autonomous Organizations, and IoT-combined smart contracts constitute coordination tools, it is the IoT-combined smart contracts that are most specific to industrial applications (i.e. Industrial IoT) and essential to Industry 4.0, as they govern communication and interactions between multiple machines which can have different owners, assuring increased efficiency and security. This capacity is particularly welcome at a time when the security of more mainstream, cloud-based solutions can be compromised and sensitive data stolen (Srivastava and Bradshaw, 2019).

A simplified model of using blockchain technology for coordinating Industrial IoT systems, quintessential of Industry 4.0, is presented in Chart 1.

Chart 1. **Simplified model of coordinating IoT with blockchain**



Source: own elaboration.

In the context of Industry 4.0, blockchain can be used to coordinate the flow of not only data but also products. Blockchain platforms built specifically for supply chains (e.g. Viant) can be used for management, control and tracking of assets along the whole supply chain, thus helping in combating counterfeit goods, preventing forced labor, environmentally unsustainable sourcing (e.g. palm oil plantations, exotic timber), and legalizing stolen goods. To be sure, the applicability of blockchain technology to Industry 4.0 production systems faces serious challenges. The first one is generic in nature and concerns high costs of producing consensus with blockchains using so-called Proof-of-Work, thus compromising scalability of the technology. However, solutions enabling much less energy-consuming Proof-of-Stake are already in place (Zmudzinski, 2019). The second challenge is more Industry 4.0-specific as the attachment of so-called RFID tags (Radio Frequency IDentification) to physical products necessary to track them takes place off-blockchain, meaning the products themselves can be tampered with. It invites efforts to incorporate identifiable and tamper-proof "signatures" at the lowest possible level, eventually the molecular level. The latter example demonstrates that the digital technology of blockchain is best complemented and integrated with advanced physical technologies, making it part of integration and cross-fertilization of digital and physical technologies, characteristic of Industry 4.0. Only then can it create bespoke coordination using trusted data and pre-programmed smart contracts.

Conclusions

Industry 4.0 manufacturing systems, using ICT to interact with and expand the capabilities of the physical systems, both demand enhanced coordination within and between organizations, and are themselves intended to improve coordination. Blockchain technology can be a part of Industry 4.0 revolution as long as it can be profitably used to such effect. The aim of this paper was to present blockchain as a novel and powerful coordination mechanism addressing the possibilities and demands of Industry 4.0 production systems and inferring its relative advantages for the Industry 4.0 manufacturing value chain.

Although blockchain is a nascent technology, its potential for becoming a new and revolutionary coordination mechanism is already evident. Whereas in "traditional" firms coordination was a major responsibility of managers (Kaldor, 1934), in the age of Industry 4.0, coordination is increasingly automated and encoded in computer algorithms. Blockchain can play an important role in the process, substituting trust in institutions with trust in algorithms, thus eliminating the traditional high costs of producing trust, related to social contracts grounded in regulatory concessions ("trusted third parties"). As increasing trust improves the efficiency of economic coordination and blockchains have the capacity to establish trust in algorithms and data with which they are fed, it can be viewed as a revolutionary new mechanism of coordination, eliminating the need for some key management functions, and using smart contracts, supported with machine learning and AI, to create bespoke coordination.

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