Blockchain and Internet of Things for Modern Business Process in Digital Economy—the State of the Art

Wattana Viriyasitavat, *Member, IEEE*, Li Da Xu, *Fellow, IEEE*, Zhuming Bi, *Senior Member, IEEE*, and Vitara Pungpapong

***Abstract*— In addition to functionalities, business process management (BPM) involves several key indicators such as openness, security, flexibility, and scalability. Optimizing system performance is becoming a great challenge for an ever-increasing large-scale distributed application system in the digital economy on the Internet of Things (IoT) era. In a centralized BPM, many indicators, such as security and openness, or cost and flexibility, are conflicting with each other. For example, inviting new partners across enterprises, domains, and regions to form a service workflow exposes new risks and needs additional security mechanisms for scrutiny; enhancing the flexibility of business workflow compositions increases the cost of security assurance. Blockchain technology (BCT) has thrown the light on the development of vital solutions to various BPM problems. BCT has to be integrated with other BPM system components that often involve IoT devices to implement specified functionalities related to the application. Currently, the potentials of using BCT have been explored although still at an early stage. In this paper, the states of the art are presented to identify emerging research topics, challenges, and promising applications in integrating BCT into the development of BPM.**

***Index Terms*— Blockchain, business process management (BPM), cyber physical system, smart contract, Industry 4.0, Internet of Things (IoT), service composition, specification language, service-oriented architecture (SoA), service selection, service workflow.**

I. Introduction

BUSINESS process management (BPM) is an approach to identify, design, execute, document, measure, monitor, and control both automated and nonautomated business processes to achieve consistent, targeted results aligned with an organization's strategic goals [124], [138]. BPM has been studied in terms of the business goals and business scopes. There are a wide variety of BPM tools available for the management of business process lifecycles and each of them has a wide assortment of functionalities [133]. The scope of BPM tools must match the business scope and the complexity of enterprise operation. While enterprise systems (ES) are becoming more complex [125]–[128], traditional BPM tools must be advanced to catch up with the emerging needs of enterprises [124]. For example, verification of transactions has become a challenging subject for the business process [136]. The activities for a business goal are used to be composed and controlled in a centralized way; in the digital economy, process control will be handed over from the process owner to all participants and no partner owns the full control of the entire business [137].

With the growth of the Internet of Things (IoT), cyber-physical systems (CPSs), and Industry 4.0, centralized BPM tools reach their limits in meeting the conflicting requirements of scalability, security, openness, and cost [131], [132]. BPM paradigm becomes decentralized. The decentralized processes have resulted in flexible processes in an open environment to promote collaboration, service sharing [141], and collective decision making [134], [140]. The advancement of information and communications technology (ICT) provides a wide range of opportunities for automating, sharing information, and transforming businesses in distributed environments [135]. The newly developed Blockchain technology (BCT) can be integrated as an essential component of the BPM solution to alleviate the issues of security, distribution, openness, and cost-effectiveness.

In this paper, we are especially interested in the research on the integration of BCT with existing IoT, CPS, and Industry 4.0 tools for the development of new-generation BPM tools in digital economy, which will have a large impact on social system in the near future [142]–[144].

II. New Development of BPM

The confluence of BCT and Industry 4.0 promises to reshape the way of how modern business processes are governed. The buzzword industry 4.0 is the logical extension of a series of technological innovations dating back to the 19th century covering interoperations, automation, Enterprise Systems (Enterprise Resource Planning, ERP), utility, and manufacturing systems. It is the congruence of computing and automation by digitalizing business processes within the

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W. Viriyasitavat is with the Department of Statistics Faculty of Commerce and Accountancy, Chulalongkorn University Faculty of Commerce and Accountancy, Bangkok 10330, Thailand (e-mail: hardgolf@gmail.com).

L. D. Xu is with the Department of IT and DS, Old Dominion University, Norfolk, VA 23529 USA.

Z. Bi is with the School of Mechanical Engineering, Indiana University, Fort Wayne, IN 46805-1499 USA.

V. Pungpapong is with the Chulalongkorn University Faculty of Commerce and Accountancy, Bangkok 10330, Thailand.

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manufacturing and service sectors. Industry 4.0 has introduced into industries the concepts of CPSs, IoT, service-oriented architecture (SoA), and BCT [42].

Most of the physical processes in modern factories can be operated under CPSs where the conditions, faults and system performances are to be real-time monitored. This implies the application of the whole IoT technology that interconnects physical and virtual things across multiple organizations to be able to communicate and work together. However, this industrial revolution requires an increasing degree of trust and privacy protection. This is where BCT comes to play, to meet the needs specific to Industry 4.0.

BCT, encouraging trust and security without traditional middle authorities or brokers, revolutionizes the interoperations among multiple parties in the cross-organizational business workflow. This technology enables the needs of transparency and distribution specifically for Industry 4.0 [44]. Transparency means that systems automatically gather and process information and make a decision through stimulating human understanding. Decentralization is the key to promote trust and security among interconnected parties, which subsequently encourages digitalization in business workflows.

One of the greatest changes that Industry 4.0 will transform traditional processes, which are carried out manually or require human decision will be undertaken by digital, autonomous systems, underpinned by BCT. For example, one of the goals for Industry 4.0 is to achieve autonomous machines. Now, if BCT is incorporated between ES or ERP and suppliers and the CPSs implemented in factories, the system can safely and autonomously place an order for their replacement. Then, the financial transactions can be triggered and realized by using smart contract, as defined with its underlying BCT, which continuously checks whether one of the previously defined contract conditions has occurred and then automatically executes certain activities [45]. This application is promising, as the success of BCT has been apparent in the form of cryptocurrency which eliminates the difficult points in the financial sector including accurate tracking of customer repayment histories, double spending, and reducing the risk of defaulters. The current outreach of BCT use cases includes streamlining asset management life cycle, eliminating fraudulent claims in insurance companies, and increasing trust and automating supply chain [30]. The integration of BCT into the business workflow will innovate business operation [46]. It is seen as one of the core technologies of Industry 4.0 with the following characteristics.

1) *Resilience:* Distributed ledgers are used to diminish the single point of failure for system resilience purpose.
2) *Scalability:* BCT-based solutions apply to any number of peers and the scale of the network in the application.
3) *Security:* Cryptography such as SHA-256, ECC, and ECDSA used in Bitcoin provide strong security for business processes management.
4) *Autonomy:* CPSs enable all components (things) to carry out transactions autonomously without the intervention of regulators or brokers.

BCT's potential is vast and has gained widespread traction and is attracting investments. In 2016, more than U.S. $2 billion have been invested in many start-up projects mostly via initial coin offerings (ICO) or Token Sales. BCT is anticipated to streamline many other business processes across industries, reducing monetary and temporal resources, and therefore, will be a foundational and fundamental piece of Industry 4.0 [42].

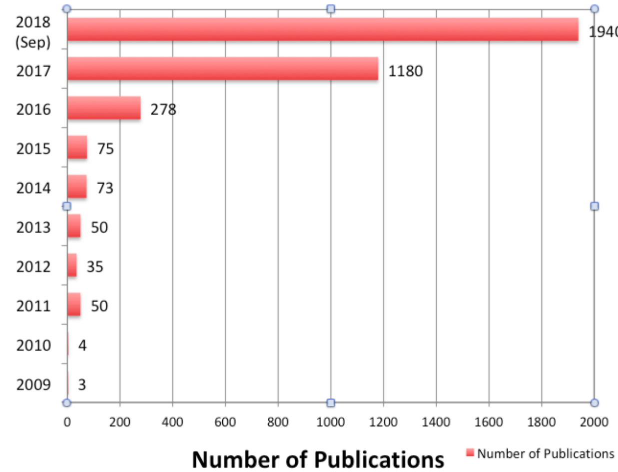

Fig. 1. Numbers of relevant publications by year.

Meanwhile, the number of BCT and IoT in business process publications is quickly growing. We conducted an extensive literature review by examining relevant articles from Google Scholar database in order to assist interested researchers and practitioners to understand the current status and future research opportunities regarding the use of BCT in business processes. Our review focuses on both identifying the breadth and diversity of existing BCT-related business process research in the industrial areas and highlighting the challenges and opportunities for future researchers. Fig. 1 shows the number of journal articles listed in Google Scholar by year from 2009 to September 2018, which indicates a trend that research on BCT in business process is becoming increasingly popular.

III. BCT in Business Process

In Industry 4.0 era, an increasing number of Blockchain applications are being tested and implemented across a range of industries, including finance, insurance, and supply chain management. A safe, permanent, and tamper-proof digital ledger of transactions is maintained and distributed across involved parties without a central broker is a key component that reshapes modern business processes and may disrupt traditional ones. To verify a new transaction, a majority of parties need to approve (verify) a new transaction before it can be recorded. Therefore, Blockchain can be seen as a replicated append-only transactional data store, which can be used to substitute for centralized brokers maintained by single trusted authorities [16].

Although the value of BCT enables new business process improvement opportunities such as replacing centralized intermediary activities, only benefits BCT offers render limited values in digitalizing and transforming business process. It requires a series of technologies including SoA, service

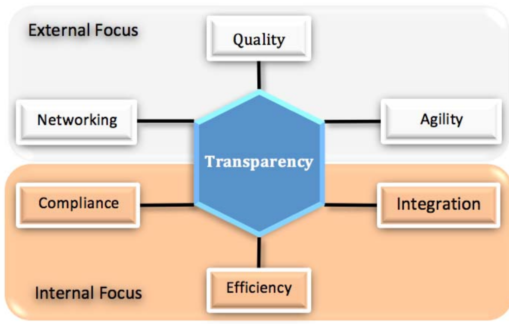

Fig. 2. Value-Driven BPM [1].

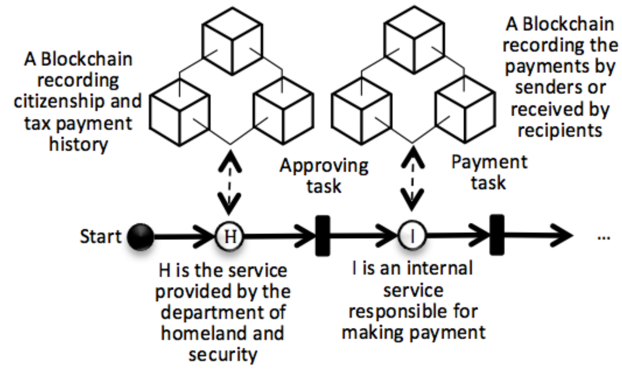

Fig. 3. Blockchain and smart contract in service workflow.

workflow and its specification languages, CPSs, and IoT together to bring value.

An overview of BCT that enables business improvement has been presented via the Value-driven BPM (VBPM) framework [1]. The framework shown in Fig. 2 classifies the BPM value into seven categories where the ultimate goal is to achieve transparency. Interested readers might see the detailed discussion on the impact and benefits of VBPM on business processes by Accenture in [139].

The first aspect is efficiency-quality that reflects the needs and expectations of stakeholders, which are fulfilled efficiently. Eyers [3], Crosby *et al.* [4], Higgins [5], [7], García-Bañuelos *et al.* [8], Weber *et al.* [22], Pilkington [31], and Prybila *et al.* [137] propose BCT-enabled solutions to increase efficiency by minimizing time and cost. In the banking industry, for example, Corda is a platform [2] creating an innovative way for current settlement. The Australian Stock Exchange [3] is implementing a system with a Blockchain-based distributed ledger to reduce costs and settlement times. In the area of supply chains, once CPSs autonomously make a decision to order for material replacement, tracking information from suppliers can be stored in Blockchain ledger, allowing resilient and accurate tracking information and preventing counterfeit products [4]. This example illustrates the integration of CPSs and BCT to deliver better value.

The second aspect focuses on agility-compliance, which refers to the adaptation ability that can quickly respond to changes. The changes can be well detected by CPSs or any monitoring system, whereas the compliance of components inside the business process can be verified by compliance checking algorithms [47]–[52]. This is where service workflow, its specification languages, and SoA technologies come to play as major components in modern business which are encapsulated and standardized in the form of services using SoA technology. BCT enhances this by using a smart contract that automatically executes certain activities as defined in its conditions. Specification languages define these conditions in a formal and unified way, which are the basic ingredients for the development of automatic compliance checking. Unless the compliance is met by the conditions, the smart contract will enforce the subsequent activities as defined in the Blockchain. For instance, Fig. 3 shows a part of the welfare payment workflow. If the conditions such as ages, citizenship verification, and tax history have been approved by the service, the confirmation will trigger the smart contract for payment. This way, the payment is more secured, auditable, and consequently trustable [53]. The example service workflow involves two tasks, i.e., approving task and payment task for two groups of participators. Therefore, two Blockchains are created to deal with the tasks, respectively.

The last aspect addresses integration-networking. BCT enables the better level of automation in the integration of inter-organizational processes as it can replace the manual processes handled by intermediaries to establish trust and confirm authenticity among previously unknown parties. For example, the use of Blockchain as a registry of products (physical and digital) to keep records and manage the transfer of the ownership of any product on distributed ledgers. This can apply to multiple areas such as land registry, healthcare, and many more, which involve the collaboration among multiple parties in business processes such as banks, government agencies, buyers, and sellers [5], [6].

In conclusion, the benefits of BCT become more apparent, which is considered to offer large potential to drastically change and improve a wide range of business processes. According to a Deloitte Survey [7], BCT is emerging as a key business focus for the U.S. companies in many industries. The aforementioned paragraphs show that potential applications of BCT for business improvement are numerous and span all seven components of the VBPM framework [16]. The role of Blockchain, served as a key substitute in established and trusted broker industries, in conjunction with a series of technologies including SoA, service workflow, specification languages, CPSs, IoT, and many others, will create significant values that open wide spectrum opportunities for research and industry sectors (see Fig. 4).

IV. Backgrounds and Research of Blockchain

Blockchain is the repository that stores the list of transactions documented as forgery-proof. The transactions to be added in Blockchain are performed by a consensus method of self-validating, meaning that no intermediaries are involved in the process. BTC, first coming to prominence in 2009 through Bitcoin, opens manifold opportunities that will change how the current business process operates. It enables the execution of collaborative business processes involving multiple

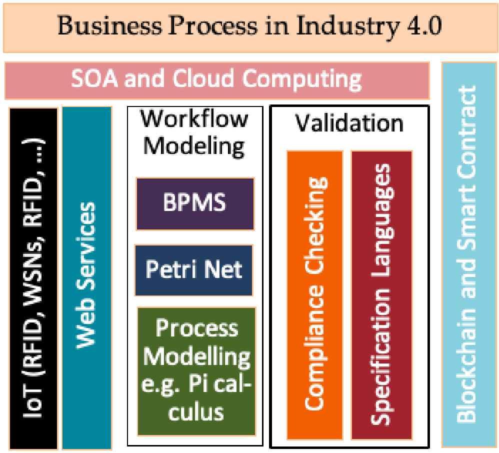

Fig. 4. Technologies for Blockchain and business processes.

dynamic untrusted services without a central authority or any particular participant [8]. Specifically, a process model comprising tasks performed by multiple services can be coordinated via smart contracts operating on the Blockchain such as Solidity [61], an executing script on top of Blockchain, in the Ethereum platform [62]. Since Blockchain maintains trust among collaborative untrusted services, the three aspects in Section III including quality-efficiency, agility-compliance, and networking-integration are greatly enhanced (see Fig. 2). To provide quality and interoperability of BCT-enabled business processes, technical standards such as SoA need to be incorporated to define the specification for data format stored in blocks. The growing number of Blockchain applications must rely on the specification as standard, which provides interoperability, compatibility, reliability, and effective operations on a global scale [15]. Many businesses and organizations are interested in the development of incorporating current standards into BCT, which will bring economic values in the future. Currently, several organizations such as IEEE project 2418 [65], ISO/TC 307 [66], and Standard Australia [17] are working on the development of various Blockchain standards. The consortium joint efforts by R3 [67] created an open-source distributed ledger technology (DLT) platform called Corda for financial services. Another initiative is a consortium led by the Linux Foundation that includes partners from finance, banking, IoT, supply chains, and manufacturing [39]. The standards will provide developers, researchers, practitioners, and users to implement Blockchain-based applications and services, which can be deployed, interoperated, and used on a large scale, and saving the development and maintenance cost in the long run. The standardization of Blockchain and related technologies will also encourage a wide spectrum of BCT and its innovations.

Nowadays, many organizations and companies have significantly invested in Blockchain initiatives. In the US, financial and technology companies led by Bank of America Corp., SBI Holdings Inc., HSBC Holdings PLC, Intel Corp., and Temasek Holdings have invested U.S. $107 million in R3 CEV (2017), a startup that runs a big bank consortium seeking to develop BCT [68]. China has announced the plans to start using BCT for collecting taxes and issuing electronic invoices [69]. Microsoft has been investing BCT and is now a founding member of the Enterprise Ethereum Alliance [70], along with other companies such as J.P. Morgan and Toyota. IBM has invested in Fabric, a Blockchain layer for enterprise solutions, which also has support from companies including Accenture, Airbus, American Express, CME Group, Intel and others [71]. Singapore government has invested U.S. $225 millions (2017) to Blockchain research and development, including Project Ubin initiative to integrate BCT into the governmental and financial apparatus of Singapore [72]. U.K. Research Council provides U.S. $4.5 million grant for Blockchain projects [73]. Almost all the countries and companies that have invested in BCT use start-up investment model by sponsoring several startups tech companies to research and develop Blockchain related solutions. In 2017, over U.S., $1.7 billion have been invested in BCT startups.

In the academic area, there are many emerging conferences and workshops in Blockchain and business processes dating back to 2017, for example, the International Workshop on Blockchains and Smart Contracts (BSC) being part of IFIP International Conference on New Technologies, Mobility and Security (IFIP NTMS) [74], IBM InterConnect 2017 focusing on developers and technical topics in emerging area especially IoT and Blockchain [75], and 2018 Crypto Valley Conference on BCT sponsored by IEEE [76].

V. Blockchain for Business Process

BCT enables the execution of collaborative business processes involving untrusted parties without a trusted authority. Tasks inside business processes are performed by multiple selected services that can be operated and validated via smart contract [8]. However, BCT itself relatively produces limited value. The innovation requires a series of integrated technologies for business process in Industry 4.0. A fundamental technology of business process is workflow modeling, which allows the creation, coordination, and validation of tasks and the involved parties responsible for task execution (executors). By using workflow modeling such as Petri Nets [24], [25], BPM system (BPMS) [54], and process models such as pi-calculus [26], business processes will be mathematically and formally modeled, such that the validation of tasks and executors can be done using specification languages [55]–[60] and compliance checking [47]–[52]. Workflow modeling technologies have been widely used with Web Services with its underlying SoA-based technology that permits seamless composition of services in the business process [129], [130]. The term service workflow is invented to define business processes that are executed using services as executors. Service workflow specification languages and compliance checking are technologies specific to this context. Everything as a service (EaaS) concept is enabled by the convergence of SoA and IoT that allows devices such as sensors, software, people, and almost everything to be able to connect to the Internet. SoA provides standards that bind together the interoperability among physical and virtual things to be seen as services, enabling a seamless integration of services that sit on top of IoT. IoT relies on many technologies behind the scene, for instance, wireless sensor networks, which

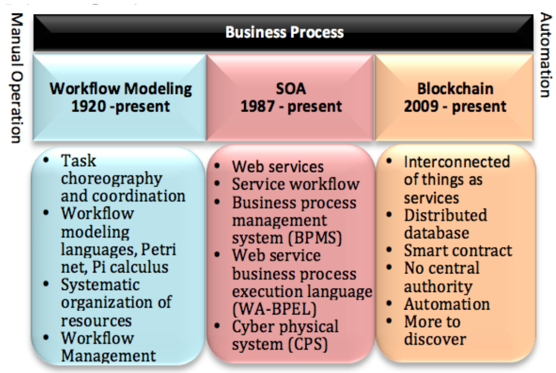

Fig. 5. Blockchain-related technologies and their impact on the business process.

mainly use interconnected intelligent sensors to sense and monitor, CPSs which allow real-time conditions and fault monitoring and replacement of equipment [63], and RFID used in logistics, pharmaceutical production, retailing, and supply chain management, since 1980s [9], [10]. The advances in SoA and IoT together with workflow-related technologies significantly contribute to the development of today's modern business processes. In addition, other technologies such as cloud computing are being used to build basic infrastructure for supporting business process 4.0. [11]–[14].

So far, BCT has been gaining attraction in industries such as finance, logistics, manufacturing, recruitment, energy management, online music, healthcare, and insurance [64]. More and more applications will be visible in the next few years. As a result, these Blockchain and related technologies have also made a large impact on new Information and Communications Technology (ICT) and ES technologies [15] (see Fig. 5.).

Blockchain enables information to be secured by cryptography that guarantees tamper-proof. Business process will receive great improvement toward automation, one of the ultimate goals in Industry 4.0. Several technologies are involved to achieve this goal. From the technology point of view, the design of Blockchain-enabled business process architecture needs to consider standardization, extensibility, scalability, and interoperability among heterogeneous services. BCT can be applied in any layer ranging from the bottommost IoT layer [42] and services layer [15] to the business process layer [21]–[23]. This section is dedicated to the application focusing on Blockchain in the business process.

In the past, BPM streamlines business processes within an organization where parties normally trust each other. However, to survive in the competitive market, businesses are seeking to collaborate with multiple organizations or businesses that have specific expertise. To establish trust among involved parties, contracts are normally used as mechanisms along with other factors such as reputation, criminal records, recommendation, and history, which are used as part of the consideration. SoA is the first wave to change the business process landscape. Business processes are modeled by service workflow where tasks are structurally coordinated, and services are executors of those tasks. SoA provides greater composition and interoperation of services on a global scale based on SoA specification and cloud computing. As the number of services is increasing and services are distributed available, business processes enter the dynamic world to face with a number of uncertainties. For example, newly available services with the same functionality have continuously emerged, existing services become obsolesce, and quality of service (QoS) is changing in time [52]. Service selection and composition to form service workflow need to consider QoS, real-time monitoring, and compliance checking to detect and replace unqualified services. The advent of IoT is a second wave as it changes the landscape of service provisions to be more decentralized and heterogeneous. IoT enables everything, such as device, sensor, hardware, software, etc., to be accessible and interconnected as a service [19], [20]. BCT is considered the third wave that has a big impact on the business process by establishing trust among untrusted services, which consequently wipe out the need of central authorities. Moreover, smart contracts enforce the execution of transactions among untrusted parties and ensure that contractual conditions are met, and obligations are enforced [8], [21], [22], [77]. By doing this, the traditional business processes that required central authorities to ensure trust will be disrupted, and new business process will be designed in a way to improve efficiency, quality, agility, compliance, and networking integration. Fig. 5 shows the conceptual architecture of Blockchain-enabled business process that consists of four major layers from the IoT layer, to the service layer, workflow modeling layer, and finally to the blockchain layer. The details of each layer are discussed as follows.

A. IoT Layer

IoT enables the interconnections among physical and virtual things via the Internet. From the functional perspective, IoT consists of four layers [15], which are: 1) Sensing layer where smart things can detect and exchange information among different devices; 2) Network layer connects all IoT things together allowing data transportation among new and existing IT infrastructure; 3) Service layer encapsulates the functionalities provided by things to be delivered in the form of services in global scale; and 4) Interface layer simplifies the management and interconnection of heterogeneous things from different vendors.

B. Service Layer

Perhaps overlapped in the IoT layer above, we separate the service layer from the IoT layer, as it is the different technology adding another layer on top of IoT. Service is based on SoA technology that provides standardization and specification of services to facilitate seamless integration among IoT things in the standard form. The main activity in the service layer involves the service specifications that mandate protocols and APIs to support interoperability. Today's ES or ERP system provides execution and monitoring of business processes, which incorporate services to take responsibility for process tasks [23]. EaaS, the term for the extensive variety of services and applications emerging for users to access on demand over the Internet, is greatly supported by IoT, cloud, and service technologies. The recent research on SoA-IoT [28] indicates service-provisioning process can facilitate interaction between services. A candidate search mechanism is used to find potential services and services are selected based on their QoS attributes in which an on-demand service provisioning mechanism will deliver a service instance that complies with requirements [15].

C. Workflow Modeling Layer

Workflow modeling layer is the heart of the business process structure. Since the economies in industrialized nations across the world have become more service oriented, a service workflow composed of several services is used to perform more sophisticated functions in the business process. The nature of dynamic interoperations allowing distributed autonomous services, such as IoT physical and virtual things, to freely enter, develop, degrade, or terminate, in an unpredictable manner, results in constant changes in the business process. Notable languages used in the workflow management system for formally defining service workflow models include Petri Net [24], [25], pi-calculus [26], UML activity diagram, WS-BPEL, or BPMN. Petri Net is the most promising one as its semantics have been demonstrated for covering the standard behavior of WS-BPEL [27]. Service workflow modeling languages along with its auxiliary technologies including workflow specification languages [55]–[60] and compliance checking of services [47]–[52] provide efficient and optimized business process solutions.

D. Blockchain Layer

Since Blockchain is designed as a basis for distributed and secured data storage that involves transaction and interactions [78], it can be applied at any layer from IoT to workflow modeling. For the impact on the service workflow-based business process evolution, we focus specifically on the use of Blockchain to gear business process towards industry 4.0. Eliminating a central authority provides a big impact on executing collaborative business processes between mutually untrusting services. Tasks being performed by multiple services can be coordinated via smart contracts, which are currently considered as the most significant mechanism for business process evolution operating on the Blockchain. Services from IoT devices or many other sources are made available using cloud or many other infrastructures. A business process is modeled and abstracted by service workflow technology and Blockchain's smart contracts enable the choreography of tasks without the need for a central authority. In reality, the contracts have a complex series of criteria to be met by services (e.g., reputation, availability, reliability, and QoS), which in this case can be specified by workflow specification languages. The languages indicate the conditions of services required for task executions in the business process. Smart contract and specification languages play a crucial role in selecting and composing services in business process 4.0. They are crucial to automatically respond based on pre-defined rules, which is essential for business process automation and ultimately decision-making.

VI. Relevant Blockchain Applications in Industries

Blockchain has currently been widely applied in the finance sector. However, the technology as being part of Industry 4.0 has its potential to revolutionize business processes in a myriad of industries. A number of industrial Blockchain and IoT projects have been conducted in several areas including banking, insurance, energy management, healthcare, voting, digital supply chain, and others. However, the applications of BCT nowadays are still in the early stage, but they continue to grow very fast. Over U.S. $15 billion have been invested into startups companies in 2017. Blockchain is currently being tested in several industries. The following presents the potential Blockchain applications for the business process 4.0 in industries.

A. Banking and Payment

Business processes for many financial industries are often centralized and controlled by trusted third party organizations. For instance, making a digital payment or transfer of money requires a bank, credit card, escrow, or other providers as central trusted authorities to complete the transaction with some amount of fee. This process is expensive and time-consuming, as well as requires complex infrastructure. Therefore, leading financial companies have invested in Blockchain. Cryptocurrencies like Bitcoin, Ethereum, etc., are prominent examples of methods for efficient money transfer. Dwolla [79], PayPal [80], and Square [81] are leading companies to adopt Blockchain to streamline alternative online payment by making it cheaper and safer. A company R3 [67], working with over 200 financial organizations, is developing a distributed ledger platform called Corda for financial services to meet standards of banking industries. SIAchain [82] is the private infrastructure, a secured and protected network created by SIA [83], to develop Blockchain applications based on DLT, which is integrated with R3's Corda platform. CorDapps (Corda Distributed Applications) [84] are distributed applications that run on the Corda platform, allowing AWS users to develop CorDapps deployed directly into the AWS market. Several other startups, for example, Ripple [85] and Stellar [86] are implementing solutions for faster monetary transfer.

B. Insurance

To a certain extent, Blockchain seems to be more revolutionary for the legal industry such as insurance than finance [87]. The global insurance market primarily relies on trust management. However, insurance companies are facing many problems of fraudulent claims, fragmented data sources, and manual processes such as multiple signatures. The use case of Blockchain in insurance involves managing trust to automatically verify many types of data in insurance digital contracts. Smart contracts have great potential to enhance several processes by offering complete control, traceability, and transparency for each claim, which further enables automatic payouts [30]. Therefore, changes are required in several parts of the business process such as verifying identity, claims management, and fraud management, to achieve automation and transparency. Integrated with IoT, Blockchain solution can efficiently solve the problem of fragmented data sources. Aeternity [29] is a project developing tools for the insurance industry based on Blockchain and IoT. It incorporates real-world data provided by Oraclize [88], a project collecting and verifying real-world occurrences and submitting this information to Blockchain to be used by insurance smart contracts. This information is known as Oracle. The core mechanism is the application of event contracts, where payment is automatically claimed when an event truly happens, as per Oracle information. This can lead to intelligent automated insurance policy applications [78].

C. Digital Supply Chain

The business process of the smart manufacturing supply chain in Industry 4.0 will become increasingly dynamic by incorporating several cutting-edge technologies such as IoT, Cloud, CPSs, SoA, and Blockchain. Currently, companies operating in supply chains establish cross-border integration through specialized intermediaries, the role played is to facilitate interoperability among various organizations. Due to the insufficiency of fundamental functionalities including standards, timestamp of transactions, monitoring and tracking of information flows and secure end-to-end delivery of information [32], typically long time-delay occurs, and cost and human errors increase. Blockchain is an ideal technology because it maintains distributed ledgers and secure point-to-point transmission, which are time stamped and tamper-proof [31]; therefore, it can reduce time-delay, cost, and human errors, encouraging transparency of the entire supply chain processes. Blockchain's DLT can also be applied to the verification of the authenticity and fair trade of products by tracking from the origin [64]. Several use cases of using Blockchain in supply chain exists [33]. Many companies are gearing towards transparent Digital Supply Chain operated under common solutions, technology, and standards for integrating business processes within a large supply chain network [32].

There are a few projects in this sector. Provenance [89] enables greater transparency by tracing the origins, histories, attributes, and ownership of products. Hijro [90], former known as Fluent, is an enterprise Blockchain network for financial institutions and global enterprises based on Bitcoin architecture. Focusing on asset trading, Hijro promises to provide accesses to powerful distributed ledger platforms for the organization. SKUChain [91] provides a total Blockchain-based solution through several products with the following features: 1) zero knowledge collaboration to enable trust with new unknown parties; 2) a platform to seamlessly integrate with current enterprise IT for supply chain called EC3; 3) tracking the flow of goods on the SKU level via Popcodes; 4) enabling transparency of business process via smart contract in Brackets; and 5) turning every financial-related information like balance sheet into Blockchain in Finance. Block verify [92] proposes another Blockchain-based solution to verify counterfeit products in the supply chain by tracking the ownership and authenticity of products along the chain.

D. Energy Management

The business process of current energy management relies on centralized authorities that use certificates to validate data among grid network. The traditional process is slow, costly, involves errors and frauds. For example, the process of data produced from the meter, logged into a spreadsheet, and transferred to the database is risky, error-prone, and might be exploitable [93].

BCT can serve as the foundation of the systems in two aspects, which in either way provides a secure system that can verify instantaneous, autonomous transactions across involved entities. In the first aspect where the most parts of energy are based on massive and centralized power plants and some parts are fed into the centralized grid, BCT could solve data management challenges without disrupting business as usual by recording transactions such as consumption and generation data directly into Blockchain. The inherent trust of data provided by Blockchain ledger can replace entirely the cumbersome processes of certificate validation. Brooklyn microgrid project [94] tested a pilot microgrid based on Ethereum platform to provide additional electricity apart from the main grid to a nearby location. Microgrid provides green energy and minimizes energy loss as estimated 5% through transmission in the U.S. [95]. The second aspect of Blockchain application is the revolution of the business process in energy management landscape. A growing number of distributed power generators and storage systems in renewables, such as solar panels and wind turbine power generators, create a new business process opportunity for direct trading between producers and customers. Energy producers and customers can purchase separately and directly without going through the trusted public grid. A number of projects, such as Power Ledger ([96] and [97]), Grid Singularity [98], EnerChain [99], and TransActive Grid [100], have adopted BCT to create P2P energy trading platforms that enable residents to choose where to buy renewable energy from their neighbors and to support communities in keeping energy resources local, reducing dissipation and increasing micro- and macro-grid efficiency [35].

IBM and Samsung [36] take a further step by incorporating IoT devices that consume electricity into Blockchain-based energy management. The autonomous decentralized peer-to-peer telemetry employs Bitcoin's underlying design to serve as a ledger of existence for billions of devices. Aiming toward the "democracy of devices" [101], which refers to distributed autonomous devices that can send messages, transfer files, and conduct transactions with one another, BCT is an ideal technology for transmission broadcast in this P2P network [102].

E. Healthcare

Most healthcare industries rely on internal process working on legacy systems, where data is kept at bay and not, or rarely, shared among authorized parties. In addition to the problem of the unsecured platform leading to sensitive information leakage, business processes are facing manual and time-consuming operations, where frauds such as insurance fraud, drug fraud, and medical fraud [103], periodically occur mostly based on false information. BCT allows medical and related parties to safely store data such as medical records and share it with authorized professionals or patients. Many Blockchain-based projects are being developed for this purpose. For example, MediLedger [104] enhances the Pharmaceutical Supply Chain by using Blockchain with the U.S. Food & Drug Administration's Drug Supply Chain Security Actcompliance. Gem [105], SimplyVital Health [106], and Tierion [107] are working on secure data sharing and access in compliance with HIPIAA.

F. Voting

The controversy of the 2016 presidential election in the USA with the interference of Russia [108] brings much concern on the trust of voting system. BCT can secure the entire process of voting starting from the registration and identity verification of voters, verifying places and other information during the voting, and counting electronic votes only for legitimate ones. Creating an immutable, publicly viewable ledger of recorded votes and liquidizing the voting process would be a big step towards making elections fair, transparent, and democratic [64].

Democracy earth [109] and Follow My Vote [110] are two startups aiming at eliminating the old-fashion voting by creating Blockchain-based online voting platforms for governments. The Bitcoin Foundation (2015) [111] has been working to develop a new project revolving around a Blockchain-based voting system. This Blockchain-based voting system was first unveiled by a Danish political party for internal elections [34].

G. Recruitment

Recruitment is another market that could be significantly improved by BCT. Hiring business process involves a significant part of verifying information that a candidate provides. This process depends heavily on manual activities by checking former-employer reference and verifying the educational certificate and CV. BCT assists the process by providing verifiable information such as a candidate's educational and work histories and qualifications in CV that would help in hiring decision. Information in Blockchain ledger is a real-time database of CVs, where the qualifications and achievements are verified and updated by the authorized hiring companies and also the university or institution that the employees graduate. This makes the hiring process cheaper, more automated, efficient, and transparent. APPII [112] in partnership with Technojobs [113] is developing verification and recruitment platforms using blockchain for CV verification.

From above, not only is the finance industry that takes benefit from BCT, some others including, insurance, digital supply chain, energy management, etc., which are currently reliant on a central authority, can all together benefit. BCT will streamline business processes because it eliminates the overhead, which is dedicated to establishing trust and validating authenticity [114].

In summary, the applications of BCT in business processes from various industries depend on the fundamental value propositions that Blockchain provides: 1) building trust from untrusted parties; 2) reducing costs by eliminating intermediaries; 3) accelerating and automating transactions that would therefore revolutionize the business process as a whole (see Fig. 6) [115].

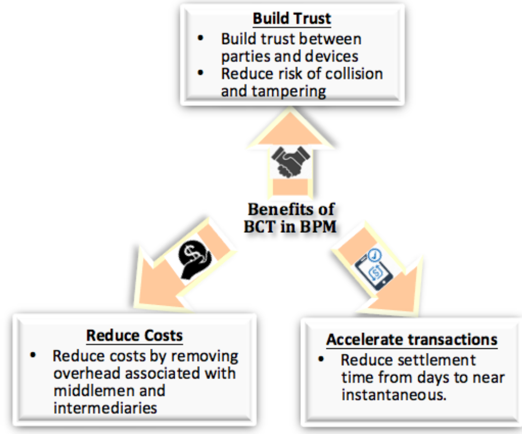

Fig. 6. Key aspects of Blockchain benefits in business processes [115].

VII. Research Challenges and Future Trends

The adoption of BCT and its smart contract is still at an early stage. The combination of BCT and BPM with underlying technologies including SoA, CPSs, and IoT can be instrumental in disrupting and revolutionizing business processes [116]. We will enter the new paradigm of business process 4.0 where services, such as IoT things encapsulated with SoA, can communicate and interoperate intelligently, dynamically, and automatically in a Blockchain-enabled service workflow.

A number of research challenges exist such as business process collaboration, large data volume, the business process using smart contract implementation, integration with specification languages, Blockchain interoperability, standardization, and security and privacy. Further efforts are needed to address these challenges. The characteristics of different industries to ensure the use of business processes 4.0 in the industrial environments need to be studied [15].

A. IoT-Based Business Process Collaboration

IoT-based business processes involve different trust issues, which can be separately addressed [37]. Blockchain smart contract offers business process to share the state of collaborations among untrusted IoT services without central intermediaries. A few techniques have been investigated for employing Blockchain to the choreography of processes. Weber *et al.* [22] introduce an approach to map a business process into a P2P execution infrastructure. Business process execution based on workflow patterns [38] and some BPMN elements is controlled by smart contract and transactions are kept in an immutable ledger. Important issues have been addressed and discussed regarding Blockchain in process execution.

B. Large Data Volume

One challenge that hinders the success of Blockchain-based business process is to handle the large volume of device-generated data and the frequency of data updates in Blockchain ledger [22]. García-Bañuelos *et al*. [8] propose a method for optimizing the business process by using parallel instantiations of smart contracts on top of commodity BCT. Other techniques in Lightning Network [117] and Plasma [118] frameworks that speed up verification in Bitcoin and Ethereum respectively, can be applied to handle large data volume. Further techniques need to be investigated depending on the characteristics of different business processes in various industries.

C. Business Process Using Smart Contract

Ethereum smart contract platform, Solidity, allows users to deploy scripts to be called by external actors to change the state of the ledger [21]. However, writing a contract into business process execution in the low level is difficult and thus is possibly limited to the professional field. There is an ongoing effort on developing a method to translate a BPMN model into a Solidity smart contract [8], [21], [22]. These works translate BPMN into Petri Net to cover all types of workflow patterns in [38]. However, not all elements of BPMN are addressed. Another aspect is the guideline of business-level language for specifying smart contract on a basis for a shared ledger Business Collaboration Language [40]. In term of usability, a smart-contract-supported platform on top of Blockchain is required for facilitating contract creation. The success factor depends on the sufficient understanding of business processes, characteristics, and requirements from various industries before the platform will be widely accepted and deployed on a global scale.

D. Blockchain and Specification Language

Modern business processes rely on real-time monitoring of attributes of services that are still complied with requirements. With ever-increasing numbers of available services, industries are facing the challenge to select preferable services for the workflow composition. Service workflow technology facilitates these by providing methodologies [41] to support business process modeling and reengineering to optimize and automate processes according to workflow requirement specifications. Compliance checking algorithms [47]–[52] provide automatic verification of the specification. These requirements are considered agreements of services to be part of business workflow. This challenge requires further investigation to translate the requirement specification into a smart contract and embedded within Blockchain.

E. Blockchain Interoperability

BCT is still in infancy where various platforms are innovated in different directions by creating their own protocols. These protocols make impossible for data exchange from one to another Blockchain. Modern business processes contain multiple distributed services to deliver functionality, which may incorporate with multiple Blockchain to achieve their goals. For example, Oracle information that represents data about real-world occurrence may be stored in different Blockchains with the different data format. Oracle information in the context of Blockchain is information that is verified regarding real-world occurrences and stored on a Blockchain to be used by smart contracts [119]. In addition, specification languages in the previous subsection may specify requirements about attributes of services, where attributes such as availability rate, reputation, etc. are kept in different Blockchains. This incompatibility prevents the scalability of Blockchain applications and then hinders the success of business process 4.0. Building an external web of connectivity in the form of interoperability protocols is one option to solve the interoperability problem. Cosmos Network [120] facilitates interoperability amongst separate Blockchains, KyberNetwork [121] focuses specifically on interoperability in financial domain, Oraclize [88] provides integration with public Blockchains including, Bitcoin, Ethereum via an HTTP API, and AlmavivA [122] is a platform to ease interconnected companies that exchange vast amounts of information.

F. Standards

As mentioned, the incompatibility of proprietary protocols creates a major problem of cross-organizational business processes. This requires standards to model the interactions and interoperations among distributed services and data stored in different Blockchains. IEEE project 2418 working group [65] is developing a standard for the Framework of Blockchain Use in IoT. ISO/TC 307 working group [66] focuses on the overall of Blockchain and distributed ledger technologies with one specific section dedicated for interoperability of Blockchain and distributed ledger technology systems. However, Blockchain standards for specific industries such as finance, insurance, etc. need further study before BCT can be widely accepted and deployed in the business process in various industries.

G. Security and Privacy

Privacy is a big concern of public Blockchain that does not guarantee any data privacy. In the scenarios of collaborative process execution, there is a trade-off between interoperability and privacy. For instance, whether the reputation score of services resided in a Blockchain ledger should be made public, or not, affects the interoperability among services in the business process workflow. Access, permission control, and management can be applied to alleviate this problem, but it comes with high overhead especially when we are in the context of global scale. However, the information stored on Blockchain is still available to all participants of the Blockchain network [22]. Authentication is another security challenge because of the great diversity and plurality of connected services, especially for IoT-based services that are susceptible to attacks and manipulations. Public Key Infrastructure can be applied but again comes with high overhead in the large scale [123]. In addition, the inherent problem of BTC is the 51% attack [35], which will have a direct effect on business process interoperation.

VIII. Conclusion

BCT has shown its great potentials to meet the conflicting requirements of security, openness, scalability, and adaptability of BPM systems in a dynamic and turbulent environment. Numerous research projects have been initialized to take advantage of BCT in different applications including financial systems, insurances, digital manufacturing, utility management, government voting systems, recruitments, and healthcare systems.

The main contributions to the presented work are as follows:

1) Recent and significant works on BCT and Industry 4.0 are surveyed, and the comprehensive survey confirmed that there is a lot of researches on the integration of BCT with BPM methods such as SoA, CPSs, and IoT. By all means, BCT-based tools will support BPM in communication and interoperations.
2) A four-layer conceptual architecture has been proposed to integrate BCT in value-driven business processes management (VBPM). The architecture shows the critical role of BCT in executing collaborative business processes between mutually untrusting services.
3) The identified research challenges for using BCT in the development of BPM tools include collaboration mechanisms, standardization, computation for a large amount of data, and BCT related smart contracts, specification languages, interoperability, and security and privacy issues.

References

[1] J P. Franz and M. Kirchmer, *Value-Driven Business Process Management: The Value-Switch for Lasting Competitive Advantage*. New York, NY, USA: McGraw-Hill, 2012.

[2] R. G. Brown, J. Carlyle, I. Grigg, and M. Hearn, "Corda: An introduction," White Paper R3 CEV, 2016.

[3] J. Eyers. *ASX Builds Blockchain for Australian Equityies*. Accessed: Jan. 25, 2018. [Online]. Available: http://www.smh.com.au/business/banking-and-finance/asx-builds-blockchain-for-australian-equities-20160121-gmbic0.html

[4] M. Crosby, P. Pattanayak, S. Verma, and V. Kalyanaraman, "Blockchain technology: Beyond bitcoin," *Appl. Innov.*, vol. 2, pp. 6–10, Jun. 2016.

[5] S. Higgins. *Republic of Georgia to Develop Blockchain Land Registry*. Accessed: Jan. 25, 2018. [Online]. Available: http://www.coindesk.com/bitfury-working-with-georgian-government-on-blockchain-land-registry/

[6] D. Palmer. *Blockchain Startup to Secure 1 Million e-Health Records in Estonia*. Accessed: Jan. 25, 2018. [Online]. Available: http://www.coindesk.com/blockchain-startup-aims-to-secure-1-million-estonian-health-records/

[7] *Deloitte Blockchain Survey 2017: Blockchain Reaching Beyond Financial Services*. Accessed: Jan. 25, 2018. [Online]. Available: https://www2.deloitte.com/us/en/pages/about-deloitte/articles/innovation-blockchain-survey.html

[8] L. GarcíBañuelos, A. Ponomarev, M. Dumas, and I. Weber, *Optimized Execution of Business Processes on Blockchain* (Lecture Notes in Computer Science), vol. 10445, J. Carmona, G. Engels, and A. Kumar, Eds. Cham, Switzerland: Springer, 2017, pp. 130–146.

[9] C. Sun, "Application of RFID technology for logistics on Internet of Things," *AASRI Procedia*, vol. 1, pp. 106–111, 2012.

[10] E. W. T. Ngai, K. K. L. Moon, F. J. Riggins, and C. Y. Yi, "RFID research: An academic literature review (1995–2005) and future research directions," *Int. J. Prod. Econ.*, vol. 112, no. 2, pp. 510–520, 2008.

[11] D. Uckelmann, M. Harrison, and F. Michahelles, "An architectural approach towards the future Internet of Things," in *Architecting the Internet of Things*, D. Uckelmann, M. Harrison, and F. Michahelles, Eds. New York, NY, USA: Springer, 2011, pp. 1–24.

[12] S. Li, L. Xu, X. Wang, and J. Wang, "Integration of hybrid wireless networks in cloud services oriented enterprise information systems," *Enterprise Inf. Syst.*, vol. 6, no. 2, pp. 165–187, 2012.

[13] F. Tao, Y. Laili, L. Xu, and L. Zhang, "FC-PACO-RM: A parallel method for service composition optimal-selection in cloud manufacturing system," *IEEE Trans. Ind. Informat.*, vol. 9, no. 4, pp. 2023–2033, Nov. 2013.

[14] Q. Li, Z.-Y. Wang, W.-H. Li, J. Li, C. Wang, and R.-Y. Du, "Applications integration in a hybrid cloud computing environment: Modelling and platform," *Enterprise Inf. Syst.*, vol. 7, no. 3, pp. 237–271, 2013.

[15] L. D. Xu, W. He, and S. Li, "Internet of Things in industries: A survey," *IEEE Trans. Ind. Informat.*, vol. 10, no. 4, pp. 2233–2243, Nov. 2014.

[16] F. Milani, L. GarcíBañuelos, and M. Dumas, "Blockchain and business process improvement," in *BPTrends Newsletter*, 2016. [Online]. Available: http://www.bptrends.com/bpt/wp-content/uploads/10-04-2016-ART-Blockchain-and-Bus-Proc-Improvement-Milani-Garcia-Banuelos-Dumas.pdf

[17] V. Meguerditchian, *Roadmap for Blockchain Standard Report*, Standard Australia, Mar. 2017. [Online]. Available: https://www.standards.org.au/getmedia/ad5d74db-8da9-4685-b171-90142ee0a2e1/Roadmap_for_Blockchain_Standards_report.pdf.aspx

[18] *The Global Venture Landscape: Decrypting FinTech*. New York, NY, USA: Goldman Sachs, Oct. 2017.

[19] L. Atzori, A. Iera, and G. Morabito, "The Internet of Things: A survey," *Comput. Netw.*, vol. 54, no. 15, pp. 2787–2805, 2010.

[20] D. Miorandi, S. Sicari, F. De Pellegrini, and I. Chlamtac, "Internet of Things: Vision, applications and research challenges," *Ad Hoc Netw.*, vol. 10, no. 7, pp. 1497–1516, 2012.

[21] O. López-Pintado, L. GarcíBañuelos, M. Dumas, and I. Weber, "Caterpillar: A blockchain-based business process management system," in *Proc. Int. Conf. Bus. Process Manage., Demo track (BPM)*, Sep. 2017.

[22] I. Weber, X. Xu, R. Riveret, G. Governatori, A. Ponomarev, and J. Mendling, "Untrusted business process monitoring and execution using blockchain," in *Proc. Int. Conf. Bus. Process Manage. (BPM)*. Rio de Janeiro, Brazil, Sep. 2016, pp. 329–347.

[23] S. Meyer, A. Ruppen, and C. Magerkurth, "Internet of Things-aware process modeling: Integrating IoT devices as business process resources," in *Proc. Int. Conf. Adv. Inf. Syst. Eng.*, 2013, pp. 84–98.

[24] D. Hollingsworth, *Workflow Management Coalition: The Workflow Reference Model*, WFMC document WFMCTC00-1003, 1994.

[25] *Workflow Management Coalition Specification: Terminology & Glossary*, WFMC document WFMC-TC-1011, Workflow Management Coalition, 1999.

[26] W. M. P. van der Aalst, "Pi calculus versus Petri nets: Let us eat 'humble pie' rather than further inflate the 'Pi hype,'" *BPTrends*, vol. 3, no. 5, pp. 1–11, 2005.

[27] C. Stahl, "A Petri net semantics for BPEL," Humboldt Univ. Berlin, Berlin, Germany, Tech. Rep. 188, Jun. 2005.

[28] H. Zhou, *The Internet of Things in the Cloud: A Middleware Perspective*. Boca Raton, FL, USA: CRC Press, 2012.

[29] Z. Hess, Y. Malahov, and J. Pettersson. (2017). *Æternity Blockchain: The Trustless, Decentralized and Purely Functional Oracle Machine*. Accessed: Jan. 23, 2018. [Online]. Available: https://aeternity.com/aeternity-blockchain-whitepaper.pdf

[30] N. Joshi. *Reinventing Financial Services With Blockchain*. Accessed: Jan. 23, 2018. [Online]. Available: https://www.allerin.com/blog/reinventing-financial-services-with-blockchain

[31] M. Pilkington, "Blockchain technology: Principles and applications," in *Research Handbook on Digital Transformations*, London, U.K.: Edward Elgar Publishing, 2015.

[32] K. Korpela, J. Hallikas, and T. Dahlberg, "Digital supply chain transformation toward blockchain integration," in *Proc. 50th Hawaii Int. Conf. Syst. Sci.*, 2017, pp. 1–10.

[33] N. Hackius and M. Petersen, "Blockchain in logistics and supply chain: Trick or treat?" in *Proc. Hamburg Int. Conf. Logistics (HICL)*, 2017, pp. 3–18.

[34] J. Millet. (2017). *Danish Political Party May Be First to Use Block Chain For Internal Voting*. NewsBTC. [Online]. Available: http://www.newsbtc.com/2014/04/22/danish-political-party-may-first-useblock-chain-internal-voting/

[35] J. J. Sikorski, J. Haughton, and M. Kraft, "Blockchain technology in the chemical industry: Machine-to-machine electricity market," *Appl. Energy*, vol. 195, pp. 234–246, Jun. 2017.

[36] V. Pureswaran, "Empowering the edge-practical insights on a decentralized Internet of Things," in *IBM Institute for Business Value*, 2015. [Online]. Available: http://www-01.ibm.com/common/ssi/cgi-bin/ssialias?infotype=PM&subtype=XB&htmlfid=GBE03662USEN#loaded

[37] W. Viriyasitavat and A. Martin, "In the relation of workflow and trust characteristics, and requirements in service workflows," in *Informatics Engineering and Information Science* (Communications in Computer

and Information Science), vol. 251, A. A. Manaf, A. Zeki, M. Zamani, S. Chuprat, and E. El-Qawasmeh, Eds. Berlin, Germany: Springer, 2011, pp. 492–506.

[38] W. W. P. van der Aalst, A. P. Barros, A. H. M. ter Hofstede, and B. Kiepuszewski, "Advanced workflow patterns," in *Proc. Int. Conf. Cooperat. Inf. Syst.* Berlin, Germany: Springer, 2000, pp. 18–29.

[39] *Hyperledger Architecture*, vol. 1, Accessed: Feb. 5, 2018. [Online]. Available: https://www.hyperledger.org/wp-content/uploads/2017/08/Hyperledger_Arch_WG_Paper_1_Consensus.pdf

[40] R. Hull, V. S. Batra, Y.-M. Chen, A. Deutsch, F. F. T. Heath, III, and V. Vianu, "Towards a shared ledger business collaboration language based on data-aware processes," in *Proc. Int. Conf. Service-Oriented Comput.*, Canada: Springer, Oct. 2016, pp. 18–36.

[41] W. Viriyasitavat and A. Martin, "The reviews and analysis of the state-of-the-art service workflow specification languages," *J. Ind. Inf. Integr.*, vol. 8, pp. 1–7, Dec. 2017.

[42] A. Bhaga and V. K. Madisetti, "Blockchain platform for industrial Internet of Things," *J. Softw. Eng. Appl.*, vol. 9, no. 10, pp. 533–546, 2016.

[43] N. Ismail. *Blockchain: Funding the Fourth Industrial Revolution?* Accessed: Feb. 5, 2018. [Online]. Available: http://www.information-age.com/blockchain-funding-fourth-industrial-revolution-123469365/

[44] N. Joshi. *Blockchain Meets Industry 4.0-What Happened Next?* Accessed: Feb. 5, 2018. [Online]. Available: https://www.allerin.com/blog/5659-2

[45] Blockchain. *Industry 4.0 and the Internet of Things*. Faizod. Accessed: Feb. 5, 2018. [Online]. Available: https://faizod.com/blockchain-industrie-4-0-und-das-internet-der-dinge/

[46] G. Hileman. *State of Blockchain Q1 2016: Blockchain Funding Overtakes Bitcoin*. Accessed: Feb. 5, 2018. [Online]. Available: http://www.coindesk.com/state-of-blockchain-q1-2016/

[47] J. Zhang, D. Kuc, and S. Lu, "Confucius: A tool supporting collaborative scientific workflow composition," *IEEE Trans. Services Comput.*, vol. 7, no. 1, pp. 2–17, Jan./Mar. 2014.

[48] W. Viriyasitavat, L. D. Xu, and W. Viriyasitavat, "A new approach for compliance checking in service workflows," *IEEE Trans. Ind. Inform.*, vol. 10, no. 2, pp. 1452–1460, May 2014.

[49] W. Viriyasitavat, L. D. Xu, and W. Viriyasitavat, "Compliance checking for requirement-oriented service workflow interoperations," *IEEE Trans. Ind. Informat.*, vol. 10, no. 2, pp. 1469–1477, May 2014.

[50] W. Viriyasitavat and A. Martin, "An improvement of requirement-based compliance checking algorithm in service workflows," in *Proc. Int. Conf. Adv. Inf. Technol. (AIT)*. Bangkok, Thailand: UACEE, 2012, pp. 41–45.

[51] L. D. Xu, W. Viriyasitavat, P. Ruchikachorn, and A. Martin, "Using propositional logic for requirements verification of service workflow," *IEEE Trans. Ind. Informat.*, vol. 8, no. 3, pp. 639–646, Aug. 2012.

[52] W. Viriyasitavat, "Multi-criteria selection for services selection in service workflow," *J. Ind. Inf. Integr.*, vol. 1, pp. 20–25, Mar. 2016.

[53] S. Higgins, *U.K. Government Trials Blockchain Welfare Payments System*. Accessed: Feb. 1, 2018. [Online]. Available: http://www.coindesk.com/uk-government-trials-blockchain-welfare-payments-system/

[54] (Feb. 1, 2018). *Business Process Model and Notation (BPMN)*. Version 2.0. [Online]. Available: http://www.omg.org/spec/BPMN/2.0

[55] D. Bianculli, C. Ghezzi, and P. S. Pietro, "The tale of SOLOIST: A specification language for service compositions interactions," in *Formal Aspects of Component Software* (Lecture Notes in Computer Science), vol. 7684, C. S. Păsăreanu and G. Salaün, Eds. Berlin, Germany: Springer, 2013, pp. 55–72.

[56] H. Davulcu, M. Kifer, L. Pokorny, C. R. Ramakrishnan, I. V. Ramakrishnan, and S. Dawson, "Modeling and analysis of interactions in virtual enterprises," in *Proc. 9th Int. Workshop Res. Issues Data Eng., Inf. Technol. Virtual Enterprises (RIDE-VE)*, 1999, pp. 12–18.

[57] S. Feja, S. Witt, and A. Speck, "BAM: A requirements validation and verification framework for business process models," in *Proc. 11th Int. Conf. Qual. Softw.*, Jul. 2011, pp. 186–191.

[58] W. Viriyasitavat, "A framework of trust in service workflows," Ph.D. dissertation, Dept. Comput. Sci., Univ. Oxford, Oxford, U.K., 2013.

[59] F-S. Hsieh and J.-B. Lin, "A self-adaptation scheme for workflow management in multi-agent systems," *J. Intell. Manuf.*, vol. 27, no. 1, pp. 131–148, 2013.

[60] W. Viriyasitavat, L. Xu, and A. Martin, "SWSpec: The requirements specification language in service workflow environments," *IEEE Trans. Ind. Informat.*, vol. 8, no. 3, pp. 631–638, Aug. 2012.

[61] *Solidity*. Accessed: Feb. 1, 2018. [Online]. Available: https://solidity.readthedocs.io/en/develop/

[62] *Ethereum Blockchain App Platform*. Accessed: Feb. 5, 2018. [Online]. Available: https://www.ethereum.org/

[63] Z. Li, Y. Wang, and K.-S. Wang, "Intelligent predictive maintenance for fault diagnosis and prognosis in machine centers: Industry 4.0 scenario," *Adv. Manuf.*, vol. 5, no. 4, pp. 377–387, 2017.

[64] *19 Industries The Blockchain Will Disrupt*. Accessed: Feb. 5, 2018. [Online]. Available: http://futurethinkers.org/industries-blockchain-disrupt/

[65] *2418-Standard for the Framework of Blockchain Use in Internet of Things (IoT)*. IEEE Project. Accessed: Feb. 5, 2018. [Online]. Available: https://standards.ieee.org/develop/project/2418.html

[66] *ISO/TC 307 Blockchain and Distributed Ledger Technologies*. Accessed: Feb. 5, 2018. [Online]. Available: https://www.iso.org/committee/6266604.html

[67] *R3*. Accessed: Feb. 5, 2018. [Online]. Available: https://www.r3.com/

[68] *International Banks Invest U.S.$107M in Blockchain Startup R3* Accessed: Feb. 5, 2018. [Online]. Available: http://business.financialpost.com/entrepreneur/small-business/payments-bofa-hsbc-intel-others-invest-107-mln-in-blockchain-startup-r3

[69] *China Will Experiment with Using Blockchain to Collect Taxes*. Accessed: Feb. 5, 2018. [Online]. Available: https://www.technologyreview.com/the-download/608570/china-will-experiment-with-using-blockchain-to-collect-taxes/

[70] *Enterprise Ethereum Alliance*. Accessed: Feb. 5, 2018. [Online]. Available: https://entethalliance.org/

[71] Bitcoin Maga-zine. *How to Slip Some Blockchain Exposure Into Your Portfolio*. Accessed: Feb. 5, 2018. [Online]. Available: http://www.nasdaq.com/article/how-to-slip-some-blockchain-exposure-into-your-portfolio-cm801471

[72] Monetary Authority of Singapore. *Project UBIN: Central Bank Digital Money Using Distributed Ledger Technology*. Accessed: Feb. 5, 2018. [Online]. Available: http://www.mas.gov.sg/Singapore-Financial-Centre/Smart-Financial-Centre/Project-Ubin.aspx

[73] *Seven Projects to Look at how Distributed Ledger Technology Could Transform the Energy Market, Banking and healthcare*. Accessed: Feb. 5, 2018. [Online]. Available: https://www.epsrc.ac.uk/newsevents/news/distributedledgertechnologytransformenergybankinghealthcare/

[74] *Blockchains and Smart Contracts Workshop (BSC)*. Accessed: Feb. 5, 2018. [Online]. Available: http://www.ntms-conf.org/ntms2018/call-for-workshops/bsc2018

[75] *InterConnect 2017*. Accessed: Feb. 5, 2018. [Online]. Available: https://www-304.ibm.com/events/tools/ic/2017ems/

[76] *Crypto Valley Conference 2018*. Accessed: Feb. 5, 2018. [Online]. Available: https://cryptovalley.swiss/event/crypto-valley-conference-2018/

[77] L. Auberger and M. Kloppmann. (May 15, 2017). *Combine Business Process Management and Blockchain*. Accessed: Feb. 5, 2018. [Online]. Available: https://www.ibm.com/developerworks/library/mw-1705-auberger-bluemix/1705-auberger.html

[78] I-SCOOP. *Blockchain and the Internet of Things: The IoT Blockchain Opportunity and Challenge*. Accessed: Feb. 5, 2018. [Online]. Available: https://www.i-scoop.eu/blockchain-distributed-ledger-technology/blockchain-iot/

[79] *DWOLLA The Ideal Platform to Move Money*. Accessed: Feb. 5, 2018. [Online]. Available: https://www.dwolla.com/

[80] *Paypal*. Accessed: Feb. 5, 2018. [Online]. Available: https://www.paypal.com

[81] *Square*. Accessed: Feb. 5, 2018. [Online]. Available: https://squareup.com/

[82] *SIAChain: The Private Blockchain for Financial Institutions, Corporates and the Public Administration*. Accessed: Feb. 5, 2018. [Online]. Available: https://www.sia.eu/en/innovation/siachain

[83] *SIA: Your Digital Payment Infrastructure*. Accessed: Feb. 5, 2018. [Online]. Available: https://www.sia.eu/

[84] *Corda*. Accessed: Feb. 5, 2018. [Online]. Available: https://www.corda.net/

[85] *Ripple: The World's Only Enterprise Blockchain Solution for Global Payments*. Accessed: Feb. 5, 2018. [Online]. Available: https://ripple.com/

[86] *Stellar*. Accessed: Feb. 5, 2018. [Online]. Available: https://www.stellar.org/

[87] *i4 Industry 4.0 Academy*. Accessed: Feb. 5, 2018. [Online]. Available: http://i4academy.com/blockchain-fintech-course/

[88] *Oraclize*. Accessed: Feb. 5, 2018. [Online]. Available: http://www.oraclize.it/

[89] *Provenance*. Accessed: Feb. 5, 2018. [Online]. Available: https://www.provenance.org/
[90] *Hijro Connects You Toa Global Network*. Accessed: Feb. 5, 2018. [Online]. Available: https://hijro.com/
[91] *SKUChain Empower My Supply Chain*. Accessed: Feb. 5, 2018. [Online]. Available: http://www.skuchain.com/
[92] *Blockverify Blockchain Based Anti-Counterfeit Solution*. Accessed: Feb. 5, 2018. [Online]. Available: http://www.blockverify.io/
[93] M. Orcutt. *How Blockchain Could Give Us a Smarter Energy Grid*. MIT Technology Review. Accessed: Feb. 5, 2018. [Online]. Available: https://www.technologyreview.com/s/609077/how-blockchain-could-give-us-a-smarter-energy-grid/
[94] *Brooklyn Microgrid*. Accessed: Feb. 5, 2018. [Online]. Available: http://brooklynmicrogrid.com/
[95] M. Lempriere. *The Brooklyn Microgrid: Blockchain-Enabled Community Power*. Accessed: Feb. 5, 2018. [Online]. Available: http://www.power-technology.com/features/featurethe-brooklyn-microgrid-blockchain-enabled-community-power-5783564/
[96] *PowerLedger*. Accessed: Feb. 5, 2018. [Online]. Available: https://powerledger.io/
[97] *PowerLedger*. Accessed: Feb. 5, 2018. [Online]. Available: https://powerledger.io/media/Power-Ledger-Whitepaper-v3.pdf
[98] *GridSingularity*. Accessed: Feb. 5, 2018. [Online]. Available: http://gridsingularity.com/
[99] J. Lilic. *The Enerchain Project*. Accessed: Feb. 5, 2018. [Online]. Available: https://enerchain.ponton.de/
[100] *TransActive Grid*. Accessed: Feb. 5, 2018. [Online]. Available: https://www.slideshare.net/JohnLilic/transactive-grid/
[101] *Device Democracy*. Accessed: Feb. 5, 2018. [Online]. Available: http://www-935.ibm.com/services/us/gbs/thoughtleadership/internetofthings/
[102] S. Higgins. *IBM Reveals Proof of Concept for Blockchain-Powered Internet of Things*. Accessed: Feb. 5, 2018. [Online]. Available: https://www.coindesk.com/ibm-reveals-proof-concept-blockchain-powered-internet-things/
[103] *Health Care Fraud*. Accessed: Feb. 5, 2018. [Online]. Available: https://en.wikipedia.org/wiki/Health_care_fraud/
[104] *The MediLedger Project*. Accessed: Feb. 5, 2018. [Online]. Available: https://www.mediledger.com/
[105] *Gem The Enterprise Blockchain Company*. Accessed: Feb. 5, 2018. [Online]. Available: https://gem.co/
[106] *Simplyvital Health*. Accessed: Feb. 5, 2018. [Online]. Available: https://www.simplyvitalhealth.com/
[107] *Tierion A New Standard For Verifiable Data*. Accessed: Feb. 5, 2018. [Online]. Available: https://tierion.com/
[108] *Russian Interference in the 2016 United States Elections*. Accessed: Feb. 5, 2018. [Online]. Available: https://en.wikipedia.org/wiki/Russian_interference_in_the_2016_United_States_elections
[109] *Democracy Earth*. Accessed: Feb. 5, 2018. [Online]. Available: https://www.democracy.earth/
[110] *Follow My Vote*. Accessed: Feb. 5, 2018. [Online]. Available: https://followmyvote.com/
[111] *Voting on the Blockchain-Version 1.0*. Accessed: Feb. 5, 2018. [Online]. Available: https://bitcoinfoundation.org/voting-on-the-blockchain-version-1-0/
[112] *APPII*. Accessed: Feb. 5, 2018. [Online]. Available: https://appii.io/
[113] *Technojobs*. Accessed: Feb. 5, 2018. [Online]. Available: https://www.technojobs.co.uk/
[114] (Oct. 5, 2017). *Blockchain's Future Outside Financial Services*. Accessed: Feb. 5, 2018. [Online]. Available: http://www.information-age.com/blockchains-future-outside-financial-services-123468925/
[115] *Watson IoT and Blockchain: Disruptor and Game Changer*. Accessed: Feb. 5, 2018. [Online]. Available: https://www-01.ibm.com/common/ssi/cgi-bin/ssialias?htmlfid=WW912350USEN
[116] B. Hughes. *The Benefits of Digital Business Process Management With Blockchain Technology*. Accessed: Feb. 5, 2018. [Online]. Available: http://www.computerweekly.com/opinion/The-benefits-of-digital-business-process-management-with-blockchain-technology
[117] *Lightning Network Scalable, Instant Bitcoin/Blockchain Transactions*. Accessed: Feb. 5, 2018. [Online]. Available: https://lightning.network/
[118] J. Poon and V. Buterin. *Plasma: Scalable Autonomous Smart Contracts*. Accessed: Feb. 5, 2018. [Online]. Available: http://plasma.io/
[119] *Blockchainhub*. Accessed: Feb. 5, 2018. [Online]. Available: https://blockchainhub.net/blockchain-oracles/
[120] *Cosmos Internet of Blockchain*. Accessed: Feb. 5, 2018. [Online]. Available: https://cosmos.network/
[121] *Kyber Network*. Accessed: Feb. 5, 2018. [Online]. Available: https://kyber.network/
[122] *Almaviva*. Accessed: Feb. 5, 2018. [Online]. Available: http://www.almaviva.it/
[123] *Industry 4.0: The Authentication of Tings Within the Internet of Things-PKI as a Solution Approach*. Accessed: Feb. 5, 2018. [Online]. Available: https://dotmagazine.online/issues/digital-production/blockchain-and-Iot/industry-4-0-the-authentication-of-things-within-the-internet-of-things-pki-as-a-solution-approach/
[124] I. Bek, "Business process management taxonomy in practice," M.S. thesis, Masaryk Univ., Brno, Czechia, 2014. [Online]. Available: https://is.muni.cz/th/420068/fi_m/thesis.pdf
[125] L. Wang, L. D. Xu, Z. Bi, and Y. Xu, "Data cleaning for RFID and WSN integration," *IEEE Trans. Ind. Informat.*, vol. 10, no. 1, pp. 408–418, Feb. 2014.
[126] C. Wang, Z. M. Bi, and L. D. Xu, "IoT and cloud computing in automation of assembly modeling systems," *IEEE Trans. Ind. Informat.*, vol. 10, no. 2, pp. 1426–1434, May 2014.
[127] Z. M. Bi, L. D. Xu, and C. Wang, "Internet of things for enterprise systems of modern manufacturing," *IEEE Trans. Ind. Informat.*, vol. 10, no. 2, pp. 1537–1546, May 2014.
[128] Z. M. Bi, "Embracing Internet of Things (IoT) and big data for industrial informatics," *Enterprise Inf. Syst.*, vol. 11, no. 7, pp. 949–951, 2017.
[129] W. Viriyasitavat, L. D. Xu, Z. Bi, and A. Sapsomboon, "Extension of specification language for soundness and completeness of service workflow," *Enterprise Inf. Syst.*, vol. 12, no. 5, pp. 638–657, 2018. doi: 10.1080/17517575.2018.1432769.
[130] W. Viriyasitavat, L. D. Xu, and Z. Bi, "The extension of semantic formalization of service workflow specification language," *IEEE Trans. Ind. Informat.*, vol. 15, no. 2, pp. 741–754, Feb. 2019. [Online]. Available: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8294213
[131] L. Xu, C. Wang, Z. M. Bi, and J. Yu, "Object-oriented templates for automated assembly planning of complex products," *IEEE Trans. Autom. Sci. Eng.*, vol. 11, no. 2, pp. 492–503, Apr. 2014.
[132] Y. Li, Z. Luo, J. Yin, L. D. Xu, Y. Yin, and Z. Wu, "Enterprise pattern: Integrating the business process into a unified enterprise model of modern service company," *Enterprise Inf. Syst.*, vol. 11, no. 1, pp. 37–57, 2017. doi: 10.1080/17517575.2015.1053415
[133] A. Meidan, J. A. García-García, M. J. Escalona, and I. Ramos, "A survey on business processes management suites," *Comput. Standards Interfaces*, vol. 51, pp. 71–86, Mar. 2017.
[134] H. Ariouat, C. Hanachi, E. Andonoff, and F. Benaben, "A conceptual framework for social business process management," *Procedia Comput. Sci.*, vol. 112, pp. 703–712, 2017.
[135] F. Rahimi, C. Møller, and L. Hvam, "Business process management and IT management: The missing integration," *Int. J. Inf. Manage.*, vol. 36, no. 1, pp. 142–154, 2016.
[136] R. Mrasek, J. Mülle, and K. Böhm, "A new verification technique for large processes based on identification of relevant tasks," *Inf. Syst.*, vol. 47, pp. 82–97, Jan. 2015.
[137] C. Prybila, S. Schulte, C. Hochreiner, and I. Weber, "Runtime verification for business processes utilizing the Bitcoin blockchain," *Future Gener. Comput. Syst.*, Aug. 2017. doi: 10.1016/j.future.2017.08.024.
[138] J. Mendling, B. Baesens, A. Bernstein, and M. Fellmann, "Challenges of smart business process management: An introduction to the special issue," *Decis. Support Syst.*, vol. 100, pp. 1–5, Aug. 2017.
[139] Accenture. (2012). *Value-Driven Business Process Management-Impact and Benefits*. [Online]. Available: https://www.accenture.com/mx-es/~/media/Accenture/Conversion-Assets/DotCom/Documents/Local/es-la/PDF2/Accenture-Value-Driven-Business-Process-Management.pdf
[140] L. D. Xu and W. Viriyasitavat, "Application of blockchain in collaborative Internet-of-Things services," *IEEE Trans. Comput. Social Syst.*, to be published.
[141] L. Qi *et al.*, "Finding all you need: Web APIs recommendation in Web of things through keywords search," *IEEE Trans. Comput. Social Syst.*, to be published.
[142] Ş. Kolozali *et al.*, "Observing the pulse of a city: A smart city framework for real-time discovery, federation, and aggregation of data streams," *IEEE Internet Things J.*, vol. 6, no. 2, pp. 2615–2668, Apr. 2019.
[143] K. R. Sollins, "IoT big data security and privacy versus innovation," *IEEE Internet Things J.*, vol. 6, no. 2, pp. 1628–1635, Apr. 2019.
[144] J. Hoffmann, P. Heimes, and S. Senel, "IoT platforms for the Internet of production," *IEEE Internet Things J.*, to be published.

Wattana Viriyasitavat (M'09) received the M.S. degree in computer engineering from Carnegie Mellon University, Pittsburgh, PA, USA, in 2006, and the D.Phil. (Ph.D.) degree in computer science from the University of Oxford, Oxford, U.K., in 2013.

He is currently an Assistant Professor with Business Information Technology Division, Department of Statistics, Faculty of Commerce and Accountancy, Chulalongkorn University, Bangkok, Thailand. His current research interests include trust, security in service workflows, specification language, Blockchain, Internet of Things, and compliance checking.

Li Da Xu (M'86–SM'11–F'16) received the B.S. and M.S. degrees in information science from the University of Science and Technology of China, Hefei, China, in 1978 and 1981, respectively and the Ph.D. degree in systems science and engineering from Portland State University, Portland, OR, USA, in 1986.

Dr. Xu is an Academician of European Academy of Sciences (Division of Engineering), and an Academician of Russian Academy of Engineering (formerly USSR Academy of Engineering). He is a 2016 and 2017 Highly Cited Researcher in the field of engineering named by Clarivate Analytics (formerly Thomson Reuters Intellectual Property and Science).

Zhuming Bi (M'11–SM'12) received the Ph.D. degrees from the Harbin Institute of Technology, Harbin, China, and the University of Saskatchewan, Saskatoon, SK, Canada, in 1994 and 2002, respectively.

He is currently a Professor of mechanical engineering with Purdue University Fort Wayne, Fort Wayne, IN, USA. His current research interests include mechatronics, automatic robotic processing, reconfigurable manufacturing, and assembling systems.

Vitara Pungpapong received the B.S. degree in statistics with the concentration in business information technology from Chulalongkorn University, Bangkok, Thailand, in 2002, the M.A. degree in statistics from Harvard University, Cambridge, MA, USA, in 2007, and the Ph.D. degree in statistics from Purdue University, West Lafayette, IN, USA, in 2012.

She is currently an Assistant Professor of statistics with the Faculty of Commerce and Accountancy, Chulalongkorn University. Her current research interests include data modeling for massive data, machine learning, and computational statistics.