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COMBINING BLOCKCHAIN AND BPMN CHOREOGRAPHIES FOR CONSTRUCTION MANAGEMENT

Alessandra Corneli[1], Berardo Naticchia[1], Francesco Spegni[1], Luca Spalazzi[2]
[1] DICEA, UNIVERSITA' POLITECNICA DELLE MARCHE, Italy
[2] DII, UNIVERSITA' POLITECNICA DELLE MARCHE, Italy

ABSTRACT

Blockchain is considered a key technology of the digital revolution and the contraposition of stakeholders in the AECO sector made it the hoped-for means to trust each other. Construction site management due to its complexity and the pluralism of the actors involved can be modelled as a BPMN choreography. This work aims to provide the construction domain with a framework for driving the digitalization of processes through exploitation of blockchains and smart contracts. The main contribution of this research is the application of blockchain for introducing trust in adversarial supply chain actors by notarizing the state of each intra-organizational process.

INTRODUCTION

Supply chain suffers from sophisticated flows of materials, information and capital that take place in a dynamic environment. This lead to the need of trustful bonds among partners in order to deliver a successful project on time and on budget (Pena et Papadonikolaki, 2019). Consistency of reporting is still a challenge and delays are experienced between monitoring and the updating of the contract status. Nevertheless the use of blockchain for the integration of the material and economic flows within construction supply chain has been only scarced investigated (Kifokeris et Koch, 2019). Blockchain is expected to revolutionize computing in several areas, particularly where centralization is unnatural as it has been demonstrated for many construction processes. The reasons for this success lie mainly in the fact that blockchains and smart contracts are perceived as tools capable of ensuring decentralized data structures for better transparency and immutability. This is due also to the fact that smart contracts can be verified by a community of independent verifiers (Turk et al., 2017).

The decentralization of most construction industry processes can find its best representation in choreographies approach for Business Process Modeling Notation (BPMN) where control over a process instance is shared between independent parties, and no party has full control or knowledge during process runtime (Prybila et al., 2017). Choreographies create also new challenges: process owners must be able to trace the execution path of a process instance across the boundaries of the different process participants. At the same time the collected information must be trustworthy to serve as legal basis for contract enforcement.

Full adoption of digitalization asks for a better management of data, where issues like integrity, provenance tracking, traceability, record keeping, change tracing and data ownership are resolved (Dimosthenis et Kotch, 2019). Blockchains are candidates to be tools able to guarantee these requirements and smart contracts are candidates to be tools capable of enforcing compliance with the agreed process steps.

This work aims to propose an approach to process management in the construction domain through the storage of all the relevant data and events produced by the different participants in a choreography process. Therefore, the solution proposed in this work consists in adopting BPMN as a modeling language providing each participant with the possibility of designing their own internal processes and notating into the blockchain the occurred events and the ended activities, so that the current state of the process of each participant remains tracked.

The original contribution of the work lays in the following aspects: 1. No work proposes to deal with both blockchain and smart contracts in order to to store the state of a business process and enforce the execution of choreography processes. 2. An interleaving semantics for BPMN choreography has been adopted in this work, which better models what happens when a blockchain is used. 3. Finally, a final contribution of this work consists in having implemented a module that derives the choreography diagram from the BPMN collaborations diagram.

BLACKGROUND

Blockchain application in construction

Despite decentralization and fragmentation are typycal of AECO sector, its strongh capacity of resisting to new technologies adoption results in a slow research and introduction of blockchain that would be highly beneficial for processes efficiency (Yang et al., 2020). On the other hand, the numerosity and different interests of actors involved in a building lifecycle demand a wide

agreement in the adoption of this new technologies. Blockchains could be part of the solution for interlinking work processes, stakeholders and assets' life cycle phases (Götz et al., 2020).

Yang et al, 2020 reported some preliminary tests in the construction domain that addressed some well known criticalities of the AEC sector such as insolvency, administration time, transparency and traceability of supply chain, and information management in general.

Blockchain is also often seen as a perfect tool for improving trust among actors involved in the construction process (Qian et Papadonikolaki, 2020).

Furthermore, the blockchain can be used to pursue quality check and compliance with regulations for materials especially with reference to components that are hidden at the end of the construction. In order to obtain a connection between the phisical world of building components and the digital framework of smart contracts and blockchain the adoption of sensors (e.g. IoT, AI, BIM) is necessary.

A thorough review of blockchain potentials in literature has been provided by the Construction Blockchain Consortium (Group FPW, 2020), which mentions transparency of transactions and reliability of data flow across the distributed supply chain among the most desired benefits induced by the integration of blockchains with the existing ecosystem of IT infrastructures and services in the AEC industry.

Anyway blockchain based technologies offer some challenges to reach a complete and fruitful application (Li et al., 2018). Firstly the correct coding of transactions and smart contracts can represent a tough task since it is error prone and can invalidate the whole process. There is also another challenge that is well-known since it affects also cryptocurrencies: energy consumption required to satisfy the proof-of-work protocol may result in big demands of computational and electrical power that become significant if digital notarization will spread throughout multiple industry domains.

Finally the AECO sector faces difficulty in introducing digital technologies because of hard training of staff. Due to the deep diffent background personnel is currently not skilled enough for an efficient adoption of the blockchain approach and the learning curve can not be ignored.

Lastly, the costs of blockchain solutions represent a major concern in adopting blockchain systems. According to all these challenges the full adoption of blockchains must move forward along with progressive digitalization of the construction processes so as all the involved stakeholders could get the necessary knowledge and skills.

Blockchain application for supply chain management

Dynamics of trust in AEC supply chains represent the perfect scenario for introduction of blockchain technology. Most of the applications and studies focused on smart contracts applications (Caldera, 2019) while blockchain could be successfully employed also in the supply chain management for smoothing the construction process, sustaining long- term trustful relationships (Shojaei, 2019). Applications of blockchains for supply chain management provide vendors and suppliers with a tool for easy exchange required certificates in an immutable and authorized way. Buyers, on the other hand, can validate those certificates as well as examine the suppliers reputation by checking their previous track records on the blockchain.

Specific means and tools for authentication of data are needed to reduce the probability of fraudulent activities throughout the supply chain. Wang et al., 2020 also worked on supply chain management developing a system for tracking information of precast constructions even if they did not focus on the connnection between physical and digital but still focusing attention construction processes more than administrative ones. Lanko et al. (2018) propose the integration of blockchain, RFID, and GPS technologies in the logistics of construction materials to the purpose of enabling the tracking of the delivery of construction materials in real-time and a more accurate prediction of delivery time, which in turn minimizes losses due to delivery delays.

The preparation of construction supply chains for blockchain requires a robust conceptualization and development of aligned operational processes with the roles and responsibilities of the stakeholders (Tezel et al., 2020).

This paper aims to suggest the application of blockchain with Business Process Modeling (BPM), where the activities of the organizations involved in a construction are formalized in the form of business processes that are first designed, and then executed by means of BPM engines. Business Process Modeling Notation (BPMN), a language for formalizing business processes, is a mature technology and its adoption by the AEC industry is increasing.

In our view, the existing BPMN provides a flexible environment where blockchain and smart-contracts can be integrated to achieve a more transparent and efficient management of the several activities going on during a construction project. This further on allows the establishment of trust between stakeholders as information about when a document was created and latest managed makes it useable as evidence of work progression.

Last but not least the blockchain assures the traceability of responsibilities and intellectual property rights, ensuring a higher speed for information exchange among actors at the same time.

METHODOLOGY

Business Process Modeling Notation

BPMN exploitation for inter-organizational processes still faces difficulties mainly owing to two limits (Ladleif et al., 2019):

1. The ownership—each participant owns and thus control its own processes but does not own and thus can not control the processes of the other participants.
2. The observability— each participant has difficulty observing the state of others' processes.

Basically BPMN has three different ways of representing processes:

- Orchestration models (OMG, 2011) typically depict the coordination of processes from a single point of view. This type of model is therefore appropriate to describe processes within a single business entity or processes where there are several participants but the control remains centralized.
- Collaboration models (OMG, 2011) show different participants and their interactions (for instance, the whole Figure 1 is a collaboration model). In other words, a BPMN collaboration model is any diagram that contains two or more participants who have a flow of messages between them. Traditionally, the message flow is assigned to message brokers or Enterprise Service Buses (ESBs) like it can be seen in Figure.1. Collaboration processes allow participants to hide actual internal processes in order to provide flexibility for internal processes to change without "breaking" the interconnections.
- Choreography processes represent a new type of model introduced with BPMN 2.0 (OMG, 2011). Its purpose is to purely represent the interaction between participants in a different format than collaboration models, focusing on the flow of messages rather than the individual detailed activities of a process.

In this regard, a BPMN choreography provides a global perspective, a kind of contract between different parties, in which each party undertakes to comply with the terms of the contract (comply with the steps of the choreography). Therefore new object types have been introduced that include sender and recipient within the object and connecting sent / received messages to this object. In presence of several independent actors, choreographic models are considered the most suitable solutions to ensure the autonomy of each individual participant in following their internal processes while maintaining control over the interaction. The choreographic models, however, still present the problem of traceability.

Blockchain and BPMN

Blockchains offer a decentralized and secure approach to tracing and control, so it is not surprising that in recent years the use of blockchains in business process management, in particular process choreography, has attracted attention. Basically, from the point of view of the integration between BPM and blockchain, the blockchain can be used as storage for the purpose of traceability or as a platform for the execution of smart contracts with the purpose of enforceability. Therefore, the solutions proposed up-to-now can be grouped into two different approaches suitable for dealing with intra-organizational processes and in two different approaches suitable for dealing with real inter-organizational processes.

- The first approach relies on using the blockchain as storage to track the events of an orchestration process. This approach has already had commercial applications (Auberger et Kloppmann, 2018)(Palacin, 2017)(Chnard, 2018)(García-Bañuelos et al., 2017)(López-Pintado et al., 2019).
- The second approach relies on using smart contracts to perform orchestration processes. This approach consists of translating the orchestration processes into smart contracts. This approach has had some success aswell, in particular Lorikeet and Caterpillar (Tran et al., 2018) are two systems that deserve a special mention.

Solutions based on this approach are appropriate to ensure enforceability for intra-organizational processes as they are centralized, but they are appropriate for neither inter-organizational choreography processes nor traceability.

- The third approach relies on using the blockchain as an immutable data storage to share the execution status of the choreography and to track events. Namely, the blockchain is used as a passive storage and as single source of truth. Weber et al. (2016) and Prybila et al. (2020) proposed to store the messages exchanged by the participants in the choreography. Hull et al. (2016) propose an artifact-centered approach. Each participant publishes its artifacts on the blockchain and can have access to the artifacts produced by the other participants.

On the one hand, this approach has the advantage of solving the problem of traceability. On the other hand, it does not solve the problem of local enforceability. Indeed, it leaves to an external application the burden of monitoring that what is notarized in the blockchain respects the steps of the choreography. This is fine only when in a consortium of several participants there is one who is the owner of the process and therefore has an advantage over the others in monitoring the execution of the process.

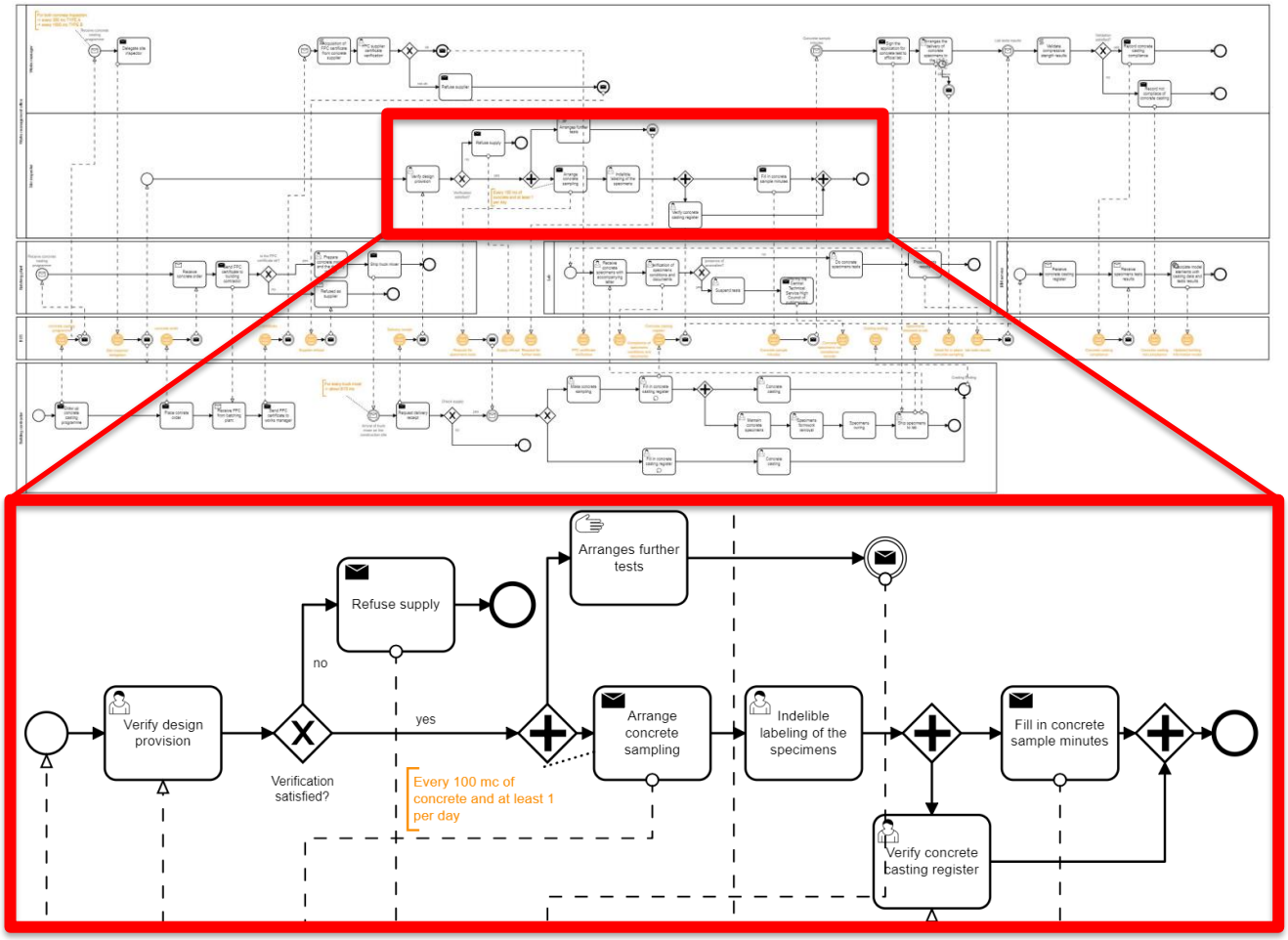

Figure 1 – Collaboration diagram of the case study and site inspector tasks zoomed in

- The fourth approach relies on using smart contracts for the enforcement of choreographies in an inter-organizational scenario. On the one hand, this approach has the advantage of solving the problem of local enforceability in a inter-organizational scenario. Indeed, the smart contract that has been obtained by the choreography controls, in a decentralized fashion, that all the partecipants comply with the choreography. On the other hand, this approach only partially solve the problem of traceability. Indeed, only the inter-organizational interactions are stored as transactions into the blockchain.

Focusing now on the construction sector, as mentioned above, the demand to face the following two challenges strongly emerges: 1. Improving efficiency and effectiveness in the construction site using business process management systems. In particular, there is a need to coordinate and control (i.e. choreograph) the activities of all participants. 2. Improving transparency and traceability.

As a matter of fact, the legislations of different countries make it mandatory to compile construction activity documentation (diaries, logs, and daily field reports), to keep track of daily activities on a construction site every day for the purpose of inspection and reporting. As far as we know, none of the solutions proposed so far satisfactorily address both challenges. Only Weber et al. (2016) and Ladleif et al. (2019) proposed a solution that partially addresses both the challenges. They both use smart contracts with functions of control and local enforcement of the choreography. This fully addresses the first challenge They both store the exchanged messages in the blockchain. This only partially complies with the second challenge. In fact, the compilation of construction activity documentation requires the tracking of all the activities carried out by the individual participants, any change of state in their processes. Just tracking the exchanged messages is not enough. The approach proposed in the present work makes complete tracking possible along with ensuring local enforcement of the choreography.

CONCRETE CASTING SAMPLING PROCESS

The case study process using in this research work regards the concrete casting sampling and verification procedure.

Figure 1 shows the process modeled with BPMN. It details all the actors involved and the tasks to accomplish, highiligthing at the same time the information flow that

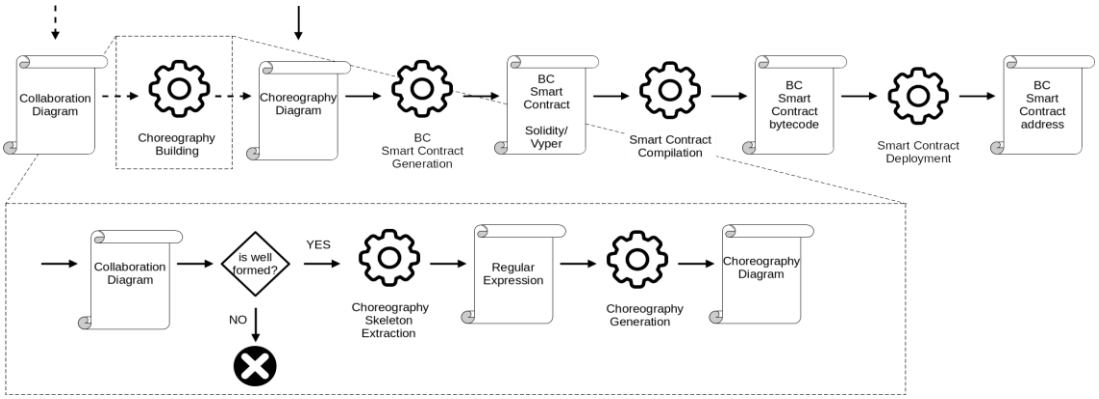

Figure 2 – Tool-chain for deploying smart contracts that notarize BPMN choreographies

occurs. For this notation Italian regulation has been taken into account, more specifically DM 17/01/2018 Norme tecniche per le Costruzioni (NTC).

This process involves four main actors who are visible in the four different pools: theWorks Management Office (WMO), coordinating the overall project and this process in particular, the Building Contractor (BC), who is in charge for realizing the final product, the Batching Plant (BP) that produces the concrete, and finally the Laboratory (L) that runs the tests for validating the concrete samplings. In the process in Figure 1 there are two additional pools: one represents the BIM service (BS) , it receives concrete test result for model enrichment, and the BUS pool which is the one where all the messages between different actors involved are received and forwarded.

A sintetic description of this complex process follows, The process begins with the BC, the BP, and the WMO exchanging two main artifacts, viz. the concrete casting programme and the FPC certificate. After a first validation of them, the WMO accepts or refuses the BP as a supplier. In case of a positive answer, the BP sends a truck mixing the concrete on the construction site and there the BC begins the concrete casting operation. According to specific conditions (Type A or Type B of concrete sampling according to NTC2018) concrete casting sampling operation is pursued with the supervision of work manager or his/her delegate. Then, after a suitable amount of time (28 days at least), the formworks are removed, and the specimens are sent to the laboratory who is responsible for concrete resistance tests. When the test results are ready, they are sent from the L to theWMO who is in charge for accepting the results.

It is easy to understand how valuable are the specimens produced along the process, and that they must be stored in a secure place in case any litigation may occur among the involved parties when a major damage occurs (e.g. the building may collapse, or decay over time). For such scenarios the benefits of securely storing such artifacts (or their integrity signature, so-called hash) on a smart-contract running on a blockchain is evident.

SYSTEM ARCHITECTURE FOR NOTARIZED CHOREOGRAPHIES AND BUSINESS PROCESSES

The system architecture here proposed combines smart contracts with business processes in order to track the relevant steps taken by the parties of a construction contract, together with the messages they exchanged along the way. The architecture assumes a federation of actors collaborating on a construction contract which is in charge of demanding the actors themselves to participate on an agreed business choreography coordinating all the necessary steps.

In this scenario, the architecture enables two main functions:

- store and enforce the correct sequence of cross-organizational choreography tasks taken by the contract parties;
- store the sequence of intra-organizational business process tasks are taken by each of the contract parties.

With the implementation of this architecture, all the parties involved in the construction contract can share a common set of information that will constitute the certified history of the contract execution making it available in the future.

The following security requirements are ensured: (i) immutability, (ii) non-repudiability, (iii) transparency, and (iv) traceability of information. In order to ensure such requirements, the architecture relies upon a nation-wise permissioned blockchain based on Quorum and available to constructor companies and contracting authorities. The architecture uses smart contracts in order to notarize both the choreography and the internal steps. As will be explained, the main difference relies on the fact that a single smart-contract is used for notarizing the choreography, and it will be derived from a business choreography attached to the (legal) construction contract, thus such smart-contract has a static nature and can introduce more checks to enforce that messages are exchanged in a pre-defined order by the participants. On the contrary, internal steps of the business process of the collaborating parties are notarized in any order, and no

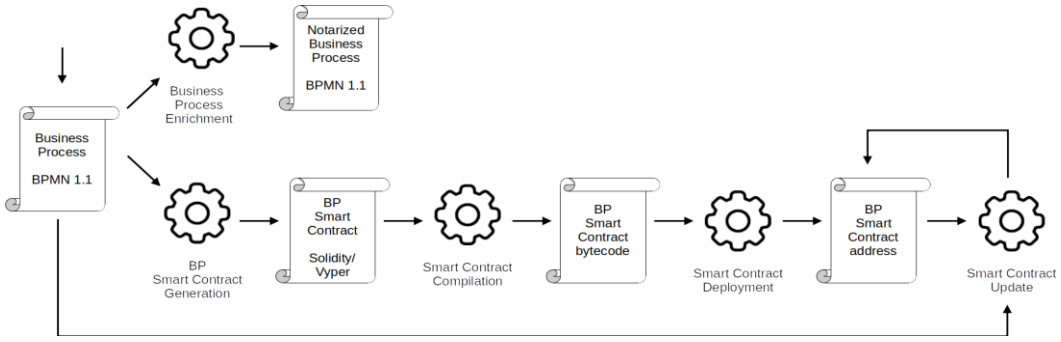

Figure 3 – Tool-chain for deploying smart contracts that notarize BPMN processes

enforcement can be done, due to the inherent variability of the operational working plans, that are subject to daily changes due to a number of unforeseeable factors. The components of the architecture for notarizing business processes and choreographies can be split onto three sets. The first set form the notarizing execution engine and is used for both notarizing business choreographies and business processes. The other two sets of components form two different development tool-chains, viz. the Choreography tool-chain and the Business Process tool-chain.

SYSTEM COMPONENTS

The notarizing execution engine

In order to allow the automatic notarization of BPMN choreographies and processes, our execution architecture is built around the state-of-the-art Camunda BPMN Workflow Engine. By means of specialized connectors, the BPMN messages can be delivered through the Quorum blockchain, so that message throw events can trigger a transaction on the smart contract that manages the choreography. Similarly, every transaction on that smart contract in turn must be delivered to the process execution engine of collaborating participants, in order to be processes as message catch events by other participants in the choreography. This is achieved by means of Camunda and a special connector that we call Quorum connector. In it, two participants contribute to the choreography each running its own process. There are then the web service layer as well as the smart contracts layer that can be seen as two different buses that processes running on different organizations can use in order to synchronize among themselves along the choreography. Obviously, the smart contracts running on Quorum natively provide high level of integrity, resilience to distributed attacks, and availability that make them more reliable than usual REST services when tracking a choreography between multiple independent parties. In order to ease the whole process we designed two development tool-chains, one for notarizing business choreographies, and the other for notarizing business processes.

The notarizing tool-chain for business choreographies

Business Choreographies (BC) in BPMN are a well known concept, especially useful when coordinating the execution of several business processes, implemented by different independent organizations that run in parallel and interact among each other and with external partners in order to provide some global task. On top of that in this work an enhanced choreography mechanism called Notarized Business process Choreography (nBC) has been defined. It maintain the records of the processes execution on a secure and trusted shared database. In order to define nBC, no extension of the BPMN 2.0 formalism is required, but a supporting architecture is needed with components supporting both designing and execution time. At development time, the following tool-chain can be used to create and deploy smart contracts then used by the execution architecture. This tool-chain is developed as follows (Fig. 2):

- Choreography Building (CB): it is an optional component, that translates a BPMN Collaboration/Orchestration Diagram onto a BPMN Choreography Diagram; it is actually an abstraction process, where several operational elements of the BPMN collaboration diagram are abstracted away, and only the exchange of relevant messages is considered; the output choreography has the property of being realized by the input collaboration diagram; this step is also useful to ensure backward compatibility of our approach (and tools) with BPMN Collaboration and Orchestration Diagrams that are still used in the construction industry.
- Business Choreography Smart Contract Generation (BC-SCG): it recognizes possible states of a choreography at any possible moments, as well as the tasks that can happen in any such state, and the actors that should execute the task; such tool takes as input a BPMN Choreography Diagram and outputs a smart contract written in Solidity or Vyper;
- Smart Contract Compilation (SCC): it translates the smart contract into its bytecode, to be run by the Ethereum Virtual Machine that is installed on every node running the Quorum blockchain;

traditionally, state-of-the-art SCC are *solc* for the Solidity language, and *vyper* for the Vyper language;

- Smart Contract Deployment (SCD): it deploys the smart contract bytecode on the Quorum blockchain network; this can be done through popular libraries such as Web3 for JavaScript and *Web3Py* for Python.

In our work we reuse existing tools for the SCC and SCD phases, resp. the compiler *solc* for the Solidity language and the library *Web3Py*, but we developed new tools for the BC-SCG and CB phases.

The notarizing tool-chain for business processes

Notarizing the internal steps of a business process enables an organization or a company that is bound by a construction contract to store transparently and on a reliable and non-repudiable medium, part of the history of the overall construction execution. As explained in previous sections, this step cannot be enforced to the participants, but it is a desired feature that many companies would benefit from.

This tool-chain helps the IT department of a single organization at development time in order to build and deploy a smart contract used to notarize the steps of a single business process. With respect to the tool-chain used for choreographies, this one produces a notarizing smart-contract that on one hand should validate the received information, and on the other must be ready for embracing a change in the definition of the monitored business process. The main steps of the tool-chain are given in Fig. 3. Among them, Smart Contract Compilation (SCC) and Smart Contract Deployment (SCD) are implemented in the same way as the notarizing tool-chain for business choreographies. The Business Process Enrichment step transforms a regular BPMN process onto an equivalent one where each process task is notarized using the process execution architecture described above. The Business Process Smart Contract Generation (BPSCG) step differs from the BC-SCG step due to the fact that organization BPMN processes are mutable objects, that adjust to unforeseen changes that happen on the construction site on a daily bases.

Finally, the Smart Contract Update (SCU) step allows to combine the dynamic changes of an organization business processes with the validation of the tasks to be notarized.

CONCLUSIONS

In the AEC domain, workplans are havily based on several parallel tasks going on, by several actors forming a federation according to a construction contract signed by all the parties. While all the tasks during construction phase can be represented by business processes, this scenario lacks a central authority that has the power or the right to coordinate all the involved actors.

Our work stems from the simple observation that the blockchain technology is a powerful tool for configuring distributed systems, and since it is based on consensus algorithms, it can ensure that all the nodes of the network can agree on a consistent linear history, realizing a distributed ledger. The information that needs to be securely stored, can be divided in two sets: pieces of information relevant to the other parties involved in the (legal) construction contract and internal steps taken by each organization or company participating in the construction process. Both kinds of information should be kept available and intact for years or decades after the construction is completed. A typical example of why this is needed is when an incident occurs and an investigation is conducted in order to recognize whether any of the parties bond by the legal contract is accountable for that.

Most of the existing works combining business processes and blockchains in literature, focus on translating BPMN Collaboration Diagrams onto smart contracts, or somehow integrate both technologies with their artifacts. In our opinion, as we have argued, the blockchain technology is better suited to enforce the execution of a distributed choreography. As future research we plan to apply the presented architecture and the prototype tools to manage some of the processes going on real-world construction sites, collecting quantitative information such as the number of monitored tasks, cooperating participants, the size of generated smart contracts, and so on.

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