

# A Smart Contract-based BPMN Choreography Execution for Management of Construction Processes

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## Abstract

Construction management can be grouped into two different levels: strategic early planning, that provides the baseline for project monitoring, and short time initiatives, based on objectives and self-organization from actors who are involved in on-site processes.

This is currently managed through the representation of many separate processes and this does not eliminate the inefficiencies that arise at the level of synchronization of the individual tasks performed by different organizations. Efficiency in construction management implies to take into consideration choreographies because they better reflect synchronization of different organizations management processes.

On the other hand, smart contracts linked to single task execution assure both promptness and irreversible tracking at single task level. The actual execution of processes depends both on what happens and on the information that flows between the subjects who actually carry out processes asynchronous to each other, so the only possibility to synchronize them is information.

This research describes a framework for applying BPMN choreographies to construction site processes in order to better model processes and integrate them with smart contracts. Every single activity in the baseline can be modelled as a choreography at a lower level. On the other hand, process performance monitoring can be performed thanks to blockchain tasks notarization.

Concrete casting quality assessment process has been chosen as use case. A BPMN choreography has been defined for this purpose and blockchain application for accomplished tasks and information notarization has been developed and tested on a construction site.

## Keywords –

Smart contracts, Process modeling, Process management, BPMN Choreographies.

## 1 Introduction

Construction site is notably a distributed environment, where each participant is responsible for running its own activities as well as business processes with tools of its choice. The passage from project scheduling to on site operations management requires a change of perspective. The latter can be considered as a complex system management issue since it presents emergent behaviors thus it can not be handled in a traditional way.

Full adoption of digitalization on the other hand asks for a better management of data, where issues like provenance tracking, traceability and record keeping are resolved [1]. Blockchains are candidates to be tools able to guarantee these requirements and smart contracts are successfully used to enforce compliance with the agreed process steps. Reasons for this success lie mainly in the fact that blockchains and smart contracts are technologies enabling decentralization of operations, better transparency, and immutability of stored information. This is implied by the fact that smart contracts must be verified by a community of independent verifiers in order to be executed[2].

This work proposes an approach to process management in the construction domain where all relevant data and events produced by different participants are stored immutably. Therefore, the solution proposed in this work is characterized by the following aspects:

1. the use of blockchain, which overcomes the need for manual data recording and ensures reliability in notarizing events;
2. the need for a domain expert formalizing choreographies of processes, checking the

- compliance of the lookahead plan, and deploying the automatically generated smart contracts on the blockchain;
3. the feasibility study of the proposed process starting from the formalization of the choreography to the application to a real case in the production and verification processes of concrete specimens.

## 2 Literature review

### 2.1 Blockchain based construction management on-site

Construction management includes the optimization of on-site operations by planning, scheduling and controlling building processes. Many scheduling methods and approaches have been proposed to manage efficiently construction, and lean production philosophy seems to be the roadmap to follow. Koskela [3] claimed the need of new conceptualization of construction that views production as a flow of materials and information to the end product. Following this philosophy, Ballard and Howell [4] proposed a new approach to construction production, and later Ballard [5] developed the Last Planner System (LPS) that performs work structuring in the control stage i.e. the process of activity identification, sequencing and scheduling. Ballard [5] proposes a scheduling process articulated into four levels of detail (Master Schedule, Phase Schedule, Look-ahead Schedule and Weekly Plan). The lookahead schedule is the most important element of the workflow control system and covers the next 3 to 12 weeks, entailing the current Weekly Work Plan.

Distributed ledger technology (DLT), or Blockchain is frequently presented as a driver of innovation in the construction sector [6]. Blockchain is a distributed ledger based on the internet. When a transaction is broadcast to the network it is received by all nodes who validate and verify its existence through a sequence of pre – defined checks [7]. Smart contracts is one major application of Blockchain in construction. It is a computerized transaction protocol that executes the terms of a contract [8]. Smart contract has the goal of satisfying common contractual conditions while minimizing exceptions and the needs of trusted intermediaries, lowering transaction costs. This tool with blockchains could be part of the solution for interlinking work processes, stakeholders and assets' life cycle phases [9]. Blockchain is also often seen as a perfect tool for improving trust among actors involved in the construction process [10]. A thorough review of blockchain potentials in literature has been provided by the Construction Blockchain Consortium [11], 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.

### 2.2 Choreographies notation for managing construction

Process-based simulation and planning are innovative techniques in the field of construction projects management. After several years of research, tools and methodologies have been developed and applied to concrete case studies, proving their effectiveness [12,13,14,15]. Compared to traditional techniques, based on PERT diagrams and Gantt charts, process-based techniques allow the generation of plans that take into consideration constraints imposed by using available resources (e.g. limited availability, non-overlapping tasks using the same resource, etc). So far, researchers focused on project management using Collaboration diagrams, using the BPMN Process notation.

Such diagrammatic representation is more suitable in case the project manager knows the internal details of the processes involved in the overall project. Construction projects, on the contrary, are examples of complex systems, where most of the internal details of involved processes are hard to elicit. For this reason, BPMN Choreography diagrams have been introduced as part of the BPMN 2.0 formalism by the Object Management Group [16]. Such diagrams more conceived about information exchange gives necessary freedom for organizations to better organize their internal processes.

Thus, BPMN Choreography Diagrams represent how the participants should interact, without introducing details on the specific process implemented by each participant. In case several suppliers or collaborators, that are external to the organization, participate in the construction process, the project manager can agree with them the expected information to be provided, the logical order in which they should be provided, and the time constraints when they should be provided; on the other side it is not necessary to know the internal steps taken by the supplier or collaborator, in order to provide such information. To the best of our knowledge, BPMN Choreography diagrams have not been used to coordinate the participants of a construction process, but several researchers have developed techniques and tools combining BPMN Choreography diagrams with the smart contracts executed on the Ethereum blockchain in order to notarize the execution steps of the processes

implementing the choreography, as well as ensuring that the choreography will be executed by the participants as expected [17, 18, 19].

### 2.3 Research questions

The fragmented world of construction involves the interaction of multiple parts from the design phase through construction till operations. During construction, in fact, multiple players participate simultaneously, which raises the question of trust between the parties and traceability of performed tasks.

In addition, on-site planning can differ from programmed planning because of instances arising from the interaction of different actors.

In the light of the just defined scenario, this research aims to respond to the need of formally represent site processes and of the notarization of the key processes steps. This is done by using the lookahead plan, well-known in construction, and translating it into a BPMN of processes. These BPMNs then act as a railway for the blockchain service as a means of traceability and reliability of information exchange among construction participants.

## 3 Methodology

Figure 1 depicts the steps of the adopted methodology. The *Choreography Definition* step analyses laws and regulations as well as international standards in order to specify how participants should interact in order to reach the overall task. In particular, it sets the documents or artifacts that are supposed to be exchanged and their expected appearance along the execution. This step is conducted by a domain expert, who collects the knowledge and represents it as a BPMN Choreography diagram. From the choreography, a smart contract written in Solidity is automatically generated and deployed on the Quorum blockchain. The *Lookahead Planning* is a responsibility of the project supervisor that, for the specific project, coordinates and schedules the on-site and off-site activities using, indeed, a lookahead plan. The lookahead plan contains detailed information about the actions to be taken by each participant, and the days when such activities are going to happen. In our methodology, the lookahead plan is extended in order to convey additional information about what documents or artifacts each participant is

expected to *produce* or *consume*, at any given activity. An example of the extended format of the lookahead plan will be given in Fig. 2. The next step is *Conformance Checking*, where the lookahead plan is compared against the choreography. This comparison yields a *positive* answer in case the participants and activities in the lookahead plan produces and consumes documents and artifacts in some order that is compliant with the given BPMN choreography. The conformance checking can be either done manually or automatically: the key idea is that the lookahead plan describing the scheduled activities can be translated onto a BPMN collaboration diagram, and the latter can be checked for compliance against a BPMN choreography using model checking algorithms [17]. In case of a negative answer, it means that the designed lookahead plan breaks laws or regulations described in the BPMN choreography, thus activities must be re-scheduled.

Finally, the *Monitoring and Notarization* step monitors the activities executed by the participant in their processes and stores the relevant information about their execution on the blockchain through the smart contract deployed in the first step.

Let us underline that the proposed methodology has two steps marked as initial, viz. *Choreography Definition* and *Lookahead Planning*. The former is taken the first time that the knowledge about laws and regulations is encoded as a BPMN choreography, and every time it changes. The latter is taken at the beginning of each construction project, and every time the project activities require a re-scheduling.

The methodology has been tested on a real case study using a prototype architecture implementing the aforementioned steps and interacting with the users using a web interface.

### 3.1 Choreography definition

A model of the inspection procedures of ready – mix concrete testing have been proposed with Business Process Modelling and Notation (BPMN) 2.0 language.

The latter is a process description language that use a flow – chart machine-readable notation. Basically, it allows to map the visual description of a process in the appropriate execution language. The advantages offered by BPMN are the following:

- flow charts to represent business and production processes;

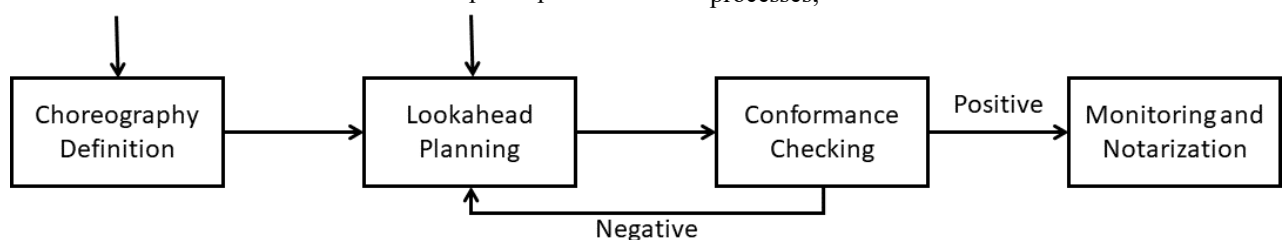


Figure 1 - Methodology steps definition

PROJECT: WAREHOUSE PROJECT			LOOKAHEAD PLAN															Information INPUT / OUTPUT	NEEDS																					
WBS	ACTIVITY	RESOURCES	03/01/2021					03/08/2021					03/15/2021							03/22/21					01/29/21															
			M	T	W	T	F	S	M	T	W	T	F	S	M	T	W	T	F	S	M	T	W	T	F	S	M	T	W	T	F	S	M	T	W	T	F	S		
	Excavation crew																																							
AM.F.EX.010	Excavation plinth no. 1F-11F	excavator 1 laborers 2	X																																					tracking finished excavator
AM.F.EX.030	Excavation w panel ground beam	excavator 1 laborers 2													X																									tracking finished excavator
	Rebar crew																																							
AM.F.RE.010	Rebars plinth no. 1F-11F	rebar crew		X	X	X			X	X	X																													lean concrete placed rebars
AM.F.RE.030	Rebars ground beams	rebar crew													X	X	X																							lean concrete placed rebars
AM.F.RE.040	Rebars w panel ground beam	rebar crew																									X	X					X	X						lean concrete placed rebars
	Concrete crew																																							
AM.F.CC.010	lean concrete foundati plinth no. 1F-11F	truckmixer concrete crew	X																																					excavation finished lean concrete order
AM.F.CC.030	concrete placing plinth no. 1F-11F	truckmixers concrete crew								X	X																						IN pouring plan (WWP) OUT DDT/transportation docs	rebars completed concrete order						
AM.F.CC.040	concrete placing ground beams	truckmixers concrete crew													X																		IN pouring plan (WWP) OUT DDT/transportation docs	rebars completed concrete order						
AM.F.CC.050	lean concrete foundati w panel ground beam	truckmixer concrete crew																									X													formworks completed lean concrete order
AM.F.CC.060	concrete placing w panel ground beam	truckmixers concrete crew																															IN pouring plan (WWP) OUT DDT/transportation docs	rebars completed concrete order						
	Works Supervisor																																							
AM.F.DL.010	quality test rebars plinth no. 1F-11F	supervisor	X																																					rebars sample
AM.F.DL.030	quality test concrete plinth no. 1F-11F	supervisor cube forms										X																					IN concrete cube forms & tags OUT concrete samples	concrete samples delivery to lab						
	Formwork crew																																							
AM.F.FO.010	Formwork ground beams	formwork crew																			X	X																		tracking finished formworks

Figure 2. The lookahead plan improved with the communication features

- standardization of flow charts components, that facilitates communication;
- a human comprehensible representation of constructs defined in software-execution language.

BPMN can be used to present three main categories of processes: orchestration, collaboration and choreography.

Orchestrations are a standard process descriptions involving a single entity executing its own tasks. Collaborations describe the interaction of several actors, attaching to each of them an orchestration. Choreographies, instead, shows only the interaction points between participants and focuses on message flows (Fig. 3).

The most important players involved in the choreography of the ready-mix concrete inspection are: Project supervisor, Site supervisor, Construction Company, Concrete supplier. Other players involved are the owner, the official tester and the local building office. The inspection procedure involves a complex set of activities, sequences and feedback processes, communication and issue of documents, as depicted in Figure 3. Starting from the mandatory steps and responsibilities identified by the NTC2018 the process has been modelled focusing on the information exchange.

### 3.2 Lookahead planning

The lookahead plan [5] is a construction stage bar chart developed by the contractor that has a time range of 4 to 6 weeks. In the Lookahead plan construction activities and single tasks are scheduled considering the needed resources.

The following set of information can be found in the lookahead plan: activities and tasks, activity timing, participants and operational resources, activity needs (predecessors, materials, tests).

The choreography definition of the inspection procedure for the selected case study needs the addition of a set of information concerning each activity. Therefore, for each activity IN and OUT information have been added, with the objective of highlighting communication needs of the inspection procedure. The lookahead plan improved with the communication features of each activity can be found in Figure 2. Activities are grouped by construction resources, i.e. crews.

### 3.3 Conformance checking

The lookahead plan contains enough information for describing the actual construction processes happening on the field. It is immediate to encode the information of the lookahead plan as a BPMN Collaboration diagram: for each crew appearing in the lookahead plan, a separate BPMN Process lane is drawn, combining the sequence of activities mentioned in the lookahead plan itself. Activities are mapped onto tasks, in the BPMN diagram, and whenever two or more activities can happen on the same day, they are translated onto tasks that are executed in parallel, using the BPMN parallel gateway. Whenever an activity A must be finished before another activity B can start, then task A is followed by task B. If two or more activities (e.g. A1, A2) must finish before the task B can begin, then tasks A1, A2 are joined together using a parallel gateway with several incoming connectors and one outgoing connector towards task B.

The input and output messages mentioned in the *Information* column are used to discriminate whenever a task is expected to throw a new message (OUTPUT) or to catch a message generated by another participant (INPUT).

A successive step is checking whether the BPMN Collaboration diagram fulfils the given BPMN Choreography diagram. In fact, the former contains the precise sequence of tasks and events that throw and catch the messages mentioned in the Choreography diagram. During the conformance checking phase, the project supervisor verifies (1) whether the sequences of messages thrown and caught as specified in the BPMN Collaboration diagram satisfy the order of messages given in the BPMN Choreography diagram, and (2) whether each message is thrown following the associated task, and is caught just before the begin of the expected task. This task can be automatized by using model checking algorithms [5].

### 3.4 System architecture

The proposed methodology has been tested using a prototype system that uses smart contracts on a Quorum blockchain to monitor the activities of processes happening on the site. The main architectural components of the system are as follows:

*Ethereum Virtual Machine.* It allows a local node to deploy new Smart Contracts on the Blockchain, and interact with them.

*Smart Contract Generator.* It translates a BPMN choreography diagram onto a smart contract written in Solidity ready to be compiled and deployed onto a Quorum blockchain.

*Smart Contract Compiler.* It allows to compile a smart contract written in Solidity onto the bytecode language interpreted by the Ethereum Virtual Machine.

*Business Process Execution Engines.* Each organization involved in the activities happening on the construction site, execute their own BPMN processes using their favourite BPMN execution engine.

*Smart Contract Connector.* It is a driver connecting the Business Process Execution Engine chosen by the organization and the Smart Contracts deployed on the Quorum Blockchain, through the Ethereum Virtual Machine. Whenever a choreography action is required the Smart Contract Connector invokes the smart contract to check whether the required exchange is compliant with the choreography encoded in the smart contract itself. In case of positive answer, the Smart Contract Connector enables the Business Process Execution Engine to do so, otherwise the connector raises an exception that will be handled by the Business Process Execution Engine.

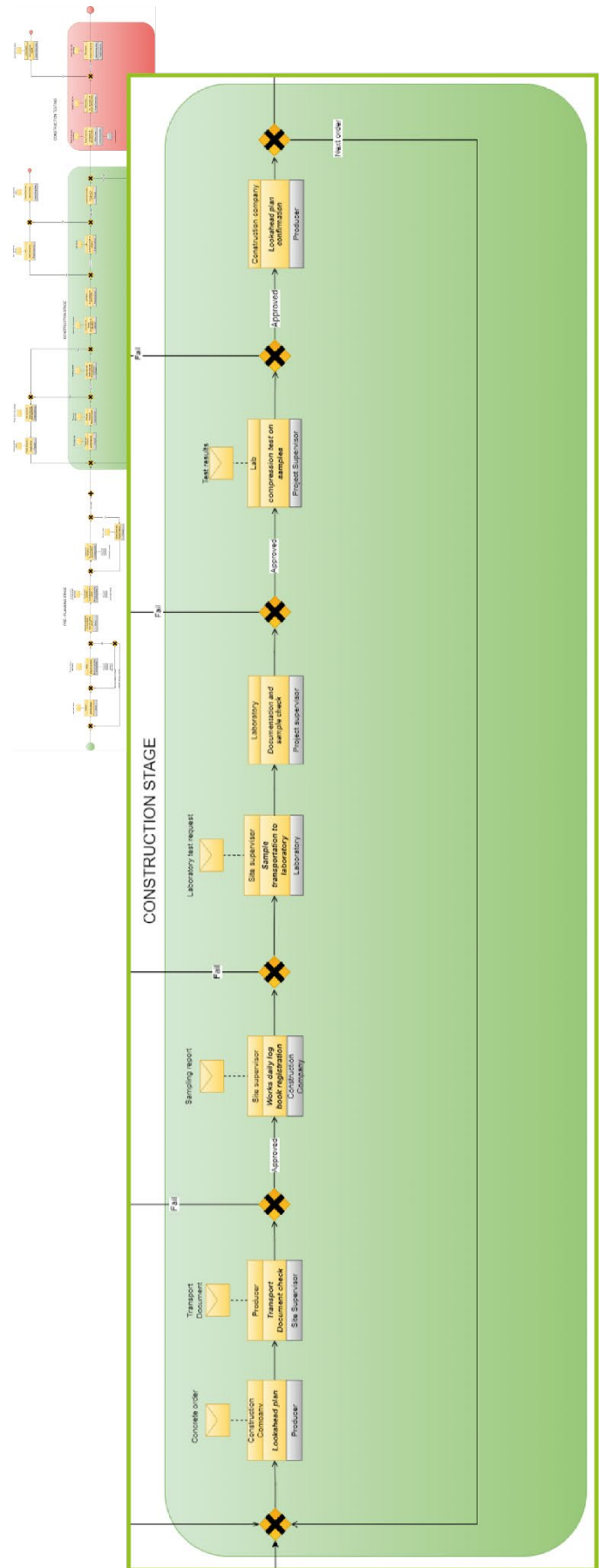


Figure 3 - Concrete test on site choreography BPMN process.

The overall system implements a so-called DApp (Distributed Application), where each organization runs its own instance of the Business Process Execution Engine, and all such instances synchronize among themselves using a single instance of smart contract deployed and running on the nodes of the Quorum blockchain. The smart contract is signed and deployed on the blockchain, thus its state is accessible to all the participants of the construction contract and not accessible to any other participant in the Quorum blockchain.

By the very definition of Quorum smart contract, each allowed participant can inspect the state of the smart contract itself at the same level of detail. This ensures that no participant is in the position of hiding information to the others, thus no participant can become a bottleneck of the information flow during the construction activity.

### 3.5 Case study

The inspection of ready-mix concrete cast-in-place process is analysed as sample case study. The cast-in-place of concrete in formworks is a very common construction sub-process, and the project supervisor must perform contract-based and regulation-based quality tests. The inspection procedure is characterized by many correlated sub-processes and implies a remarkable modelling complexity. Furthermore, the

inspection of ready-mix concrete cast-in-place is a critical task for detecting a building structure quality and therefore needs to be assessed by several documents, following national standards, regulations and guidelines. The case study of the construction of a large warehouse building in northern Italy has been used to test the proposed method. The warehouse building structure is made of prefabricated components of reinforced concrete and has a one / two storey hall-like shape. The load bearing structure is made of a prefabricated reinforced concrete frame system (columns and beams), the envelope is made of reinforced concrete prefabricated wall panels and corrugated roof metal slabs. The foundations are individual spread footings for each column, joined together by ground beams, made of reinforced concrete. The project quality test of the conversion process of ready mix cast-in-place reinforced concrete construction of the foundations has been used to test the proposed system. The inspection procedures are defined by the Italian technical regulation of construction [20]. The ready mix quality test consists in taking a sample of concrete during pouring operations. A cube – shape formwork, of 150 mm of side is filled with concrete, delivered to an accredited structural mechanics laboratory. According to the regulation then the laboratory will perform a compression resistance test on the sample after 28 days from the preparation and not

The screenshot shows a web application interface for a workflow task. The main content area displays a form for 'Concrete samples' with the following fields and options:

- Latitude:** 43.5942
- Longitude:** 13.5034
- FILE** (Photo)
- skip
- notes:** required if skip this step

The right sidebar contains details for 'Concrete Sample Process #11' and 'Supplier #11':

- Concrete Sample Process #11:** Flow: Concrete samples, Status: NEW, Created: July 19, 2021, 9:21 a.m., Name: CANTIERE TEST
- Supplier #11:** Created: July 19, 2021, 9:31 a.m., Modified: July 19, 2021, 9:31 a.m., Name: Gregoriotti Edilizia, Vat / Fiscal Code: 25663014, Address: via Circonvallazione 6, City: Ancona, Zip: 60124, Country: Italy

The bottom of the form has 'SAVE' and 'NEXT' buttons.

Figure 4. Web app screen of transport document request



later than the following 45 days. The aim of this first application is to test the notarizing process system with the delicate process of concrete mixing test that involves different figures and presuppose trust.

The choreography designed for the case study (see Fig. 2) involved 8 actors: Designer, Owner, Project Supervisor, Municipality, Construction Company, Concrete Supplier, Site Supervisor, and Laboratory. It includes 21 user tasks, one start event, two terminating events, 15 parallel gateways, 41 flow arrows connecting tasks and gateways among themselves, 17 produced documents and 4 returned receipts.

#### 4 On-site feasibility test

The experiment conducted at the site involved notarizing all steps of the concrete testing choreography. A web application was developed to allow notarization of the various steps on site directly via smartphone or tablet. The part of the entire modeled choreography that was possible to test live on site begins at the arrival of the concrete mixer truck and is highlighted in green in Fig. 2.

The web app requires a log-in procedure so it presents different screens depending on whether the person logging in is the project supervisor or the lab performing the testing for example. Once the new process has been created, the first information to be noted is that concerning the concrete supplier company. In Figure 4 it is possible to notice that in this phase also the transport document can be uploaded as an image and then sent to the blockchain service to be stored immutably.

At this point we proceeded with the actual formation of the concrete specimens whose images can be seen in Figure 5. It was possible to upload and notarize a picture of the tested concrete specimens in the application.

In the case study a sample concrete cube from the truck mixer has been prepared during the pouring of a spread footing of the foundations of the building.

To the aim of digitalizing the testing process a RFID digital tag has been used to identify the cube sample. The RFID tag has the size of a coin and has to be placed on the surface of the concrete cube.

In this case the photo, Figure 5, was particularly useful because the concrete specimens were provided with an RFID tag in order to verify their identity once transported to the laboratory. The photo is therefore useful to verify the correct positioning of the tag.

Finally, the reading of the RFID tag together with the geographic coordinates of where it happened have been notarized by reporting the identification code of the passive instrument inserted in the specimen.

The last document of this part of the process to be noted is the report of the results of the compression test of the concrete mix. The test aimed at demonstrating the feasibility of the presented methodology. It should be specified that prior to the on-site test, training was given to the figures involved, with particular reference to the project supervisor, who was in charge for carrying out most of the operations.

#### 5 Conclusions

The introduction of a rigorous translation of construction industry processes through standards is still slow in coming while it could be a valuable tool within a sector characterized by high fragmentation. The aim of this work has been to propose a methodology to integrate process modeling through BPMN with smart contracts. This has the advantage of being able to attest reliability and accountability in the completion of tasks. Starting from the case study that in this case has focused on the construction phase and in particular on a delicate process rich in infiltration as concrete quality control, a blockchain has been proposed for the notarization of the information flow.

For modeling of construction management processes, we started from the application of traditional tools such as the lookahead plan and then proceeded to the translation into BPMN. The first process modeling made use of BPMN Collaboration then translated to BPMN Choreography since the latter representation better mimics the structure of construction industry. In our case study, compliance between the BPMN Collaboration diagram and the BPMN Choreography

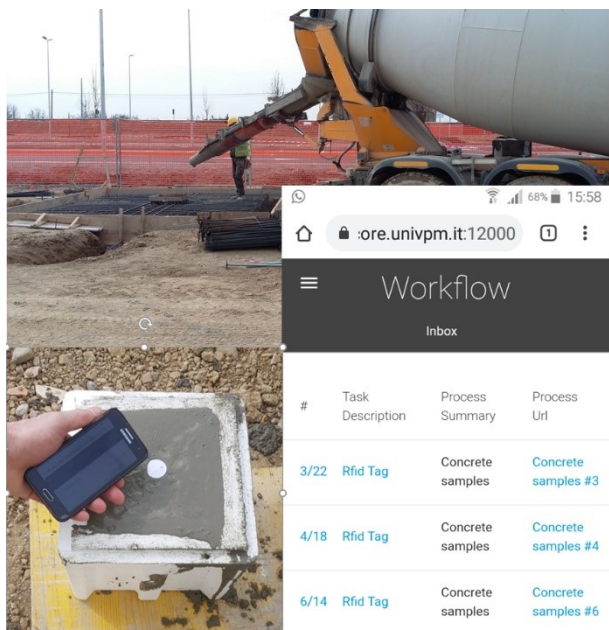


Figure 5. Clockwise from top to bottom: concrete mixer for casting concrete foundations; webapp for blockchain; on site concrete specimen with rfid read with smartphone.

diagram was conducted manually. We leave as future research the implementation of automated procedures to conduct this comparison.

A web application was then developed to map the modeled process to annotate the flow of information between the different actors in the process, which in this case were the project supervisor and the testing laboratory.

The whole proposed system was tested in a construction site in northern Italy in order to evaluate the feasibility on site and to investigate possible fraud attempts. While this test focused on a specific choreography of processes, the presented methodology can easily be applied to other construction processes, in order to test its extendibility and effectiveness.

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