Exploring the Path Towards Construction 4.0: Collaborative Networks & Enterprise Architecture Views

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Abstract. Construction 4.0 is an engineering and construction paradigm derived from Industry 4.0 that describes the fourth industrial revolution. Construction 4.0 promises to revolutionize the way buildings are constructed and managed; however, there are several major hurdles to be overcome, such as the human skilling and degree of automation, the information systems aspect, and especially the heterogeneous nature of the projects and the supply chains involved. This paper elaborates on these challenges in achieving the Construction 4.0 paradigm and describes possible solutions using various concepts based on Collaborative Networks and Enterprise Architecture disciplines to enable the full potential of the Construction 4.0 paradigm.

Keywords: Construction 4.0, Collaborative Networks, Enterprise Architecture.

1 Introduction

Construction 4.0 is an engineering and construction paradigm derived from Industry 4.0, covering "the industrial use of new construction systems and digital technologies on projects and in structures delivered" [1]. Furthermore, it calls for new professions and skills in the construction sector as a result of the adoption of new digital technologies. These technologies encompass (a) *industrial production systems* such as prefabrication, 3D-printing and assembly, and offsite manufacture; (b) *cyber-physical systems* incl. sensors, drones, autonomous vehicles, and robots; and (c) *digital technologies* like BIM (building information modelling), laser scanning, AI and cloud computing, big data and data analytics, blockchain, and augmented reality) [2].

The *Construction 4.0 paradigm* promises to revolutionize the way buildings are constructed and construction sites are managed. While the awareness and readiness of construction professionals steadily improve [3], there are still major challenges ahead to be overcome by this traditional heavy industry. Some of these challenges have been identified by Oesterreich & Teuteberg [4]: (a) the complexity of construction projects, (b) the uncertainty over tangible and intangible constraints within the individual projects, (c) a highly fragmented supply chain, (d) short-term thinking as a result of the temporary nature of construction projects, and (e) rigid culture, resistant to changes.

This paper elaborates in the following opportunity areas for the construction sector: (a) technology-enhanced construction management *functions* towards more fluid, faster projects with fewer errors, (b) interoperable *information* management systems for effective communication and coordination, (c) improved human *resources* digital skills towards the construction worker of the future, and (d) better approaches for the dynamic *organisation* and management of the construction supply chains, guided by the disciplines of *Collaborative Networks* [5] and *Enterprise Architecture* [6].

2 Technology-Enhanced Construction Management Functions

Digital Transformation of the construction sector, as one of the oldest industries [7], represents a significant set of opportunities for the effective management of construction projects, and the improvement of their productivity and supply chains [7-9]. According to [8], the *Construction 4.0 design principles* can be summarized in (a) *interconnection and interoperability* – aimed at supporting effective communication and coordination among stakeholders; (b) *information transparency* – enabled by virtual and augmented realities; (c) *decentralized decision-making* – using cloud-based building information systems for collaboration throughout a building lifecycle, and (d) *technical assistance* – by robots and drones usage for hazardous and unsafe works for humans as well as new human-machine collaborations for higher levels of productivity than neither can achieve in their own. Furthermore, the *Operational and Informational Technologies* (OT/IT) in the construction sector can be categorized into three big groups according to [9]: (a) *workflow automation technologies* – focused on improving structured data manipulation and handling such as CAD, ERP, CRM, and more recently BIM (Building Information Modelling[*]) systems; (b) *communication and collaboration technologies* – focused on enhancing the handling of unstructured data (like text, voice, images, and videos) by using (i) big data analytics for better understanding customers' expectations, (ii) augmented reality for very informative and interactive e-brochures, (iii) virtual reality for mock-ups walk-throughs, and (iv) wearable devices for anywhere, anytime communication, coordination and collaboration among stakeholders; and (c) *operational technologies* – spanning from (i) smart sensors for real-time data acquisition, (ii) fast building systems based on prefabrication, preassembly, modularization and 3D-printing approaches, and (iii) robotics and automation for performing repetitive and/or dangerous processes for humans, and artificial intelligence for aiding construction workers with smart equipment and tools to do better their jobs.

Moreover, Hossain & Nadeem [8] propose a *strategic framework* to implement the *Construction 4.0 paradigm* at supply chain level among construction companies by following a step-by-step procedure that (a) maps out the construction supply chain and its digital maturity; (b) selects construction partners for a pilot project; (c) builds digital capabilities by incorporating new construction technologies to the supply chain partners' bag of assets; and (d) starts performing data analytics towards a data-driven decision-

[*] BIM is a digital representation of the physical and functional characteristics of a facility, and a shared, reliable knowledge resource for decision-making about a faculty during its lifecycle [10].

making culture; finally (e) transforms and (f) sustains a new digital way of operating using appropriate digital tools and standards for higher productivity levels.

3 Interoperable Information Management Systems

BIM [10] is becoming the core of information management in the construction industry to allow all stakeholders to exchange and manage information throughout the lifecycle of a building. Unfortunately, however, the BIM adoption rate in the construction sector has been much slower than anticipated [11], even though BIM offers the capability of *digitising* building projects information based on established information technologies within the various professional areas involved in the building lifecycle phases. Thus, BIM is an essential component of new *Cyber-Physical Building Management Systems (CP-BMSs)* proposed by Noran et al. [12], which constitute a major stepping stone towards the *Construction 4.0 paradigm* attainment. Hence, a *CP-BMS* can be defined as “a building management system that leverages the advances brought by intelligent cyber-physical systems for real-time information management of a building state during its lifecycle” [12].

Importantly, the full benefits brought by CP-BMSs and BIM can only be achieved if *digital technologies* facilitate the prompt and free flow and ubiquity of information among construction stakeholders under cloud-based interoperable information systems [13], whereby the appropriate *cloudification* and *interoperability standards* have to be achieved in terms of structure [14] and extent [15] (see Fig. 1). Also, the use of large amounts of information gathered by smart sensors towards data-driven decision-making poses the challenge of proper interpretation to achieve self- and situational-awareness as described in [12] and [16], possibly using situation and domain level theories through channel logic [17] as further detailed in [18].

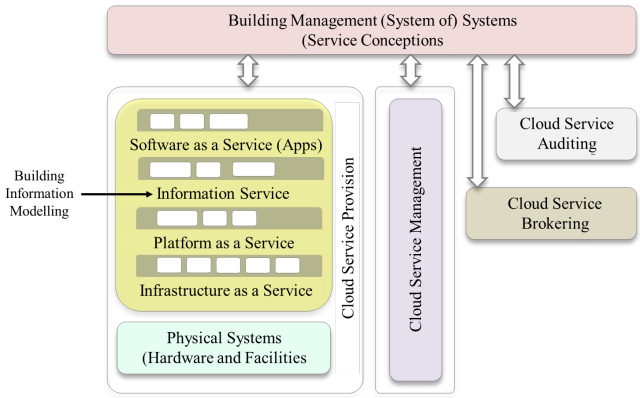

Fig. 1. CP-BMS and BIM Cloudification (based on the model described in [12])

3 Human Resources Digital Skills Development

Although more *digital skills* are gradually starting to be demand in the construction sector, there is still a high degree of resistance to change in this traditional industry [3].

In this sense, the *Operator 4.0* concept defined by Romero et al. [19] can be specialised to define several stages in the development of a construction worker skillset towards the *Construction Worker 4.0,* as follows: (stage 1) construction workers continue to conduct manual and dextrous work with support from mechanical tools and manually operated machines; (stage 2) construction workers make use of computer-aided tools such as CAD systems, possibly integrated into other enterprise information systems like ERPs, and motor-powered construction machinery; (stage 3) construction workers get involved in cooperative work with robots, drones, and other machines and computer tools in human-robot collaborations; and (stage 4) construction workers evolve to the usage of wearable devices enhancing their physical, sensorial, and cognitive capabilities.

In this fourth stage, the construction worker evolution is represented by a *smart* and *skilled* operator who performs work aided by machines *if* and *as needed*. Automation here is seen as a further enhancement of the human's physical, sensorial, and cognitive capabilities through the usage of *Human Cyber-Physical Systems (H-CPSs)* [19, 20]. The implementation of the *Construction Worker 4.0* concept would evolve the current state of human-machine interaction in the construction sector, and thus, become an essential enabler for the *Construction 4.0 paradigm.* Moreover, the application of the *Human-in-the-Loop (HITL)* feedback control systems in construction projects can lead to systems that require human interaction [20] by (a) letting the operator directly control the operation under supervisory control, (b) letting automation monitor the operator and take appropriate actions, or (c) a hybrid of 'a' and 'b', where automation monitors the operator, and takes human input for the control and acts appropriately. HITL control models, although being challenging due to the complex physiological, sensorial, and cognitive nature of human beings, are an important enabler for the achievement of the *balanced human-automation symbiosis,* especially in the construction sector where there is a usually featuring hesitation and delays in adopting robotics and automation technologies.

4 Dynamic Supply Chain Organization and Management

The construction sector has traditionally been known for custom-built projects for one-off designs; unfortunately, this tradition constitutes an important challenge in achieving the *Construction 4.0 paradigm* as, for example, *new industrial production systems* like "fast building systems" based on prefabrication, preassembly, modularization and 3D-printing, and *advanced operational technologies* like construction automation [21] and robotics systems would benefit from more standardization and usage for higher levels of productivity and construction quality.

The construction industry is one of the major raw materials consumers; moreover, its products (i.e. buildings) account for 30% of global greenhouse emissions [22]. In the current climate change situation. and efforts to control it, (a) waste minimization during construction and (b) the creation of sustainable and energy-efficient buildings is paramount [23]. The *Circular Economy* concept, populated with interconnected sensing enterprises, intelligent assets, and CPSs [24] can help meet these goals. Unfortunately, however, a significant barrier in achieving the necessary circularity and efficiency is the heterogeneity of the suppliers involved in the construction effort, resulting in quality control, time, and budget issues. Concepts such as *Logistics 4.0* attempt to address the issue [25], however, they are mainly snapshot-based and focused on technology rather than taking a holistic, lifecycle-based approach, and also including other important aspects such as “human aspects” with automation boundary or distinction between management and production activities [26].

5 Collaborative Networks and Enterprise Architecture Views

5.1 Collaborative Networks Models in the Construction 4.0 Context

This paper proposes to engage the concept of *Collaborative Networks (CNs)* [5], which has been proven in various areas and now is reaching the Industry 4.0 paradigm as communities or ecosystems of smart entities [27]. CNs have been traditionally used to allow collaborative enterprises to bid for one-of-a-kind projects requiring competencies beyond those of a single organisation [28]. Many construction projects such as large buildings (or clusters thereof) or infrastructure (i.e., roads, bridges, tunnels) fit this image. In addition, the management of the completed buildings can also benefit from the CNs virtual enterprise models in the form of potential *Service Virtual Enterprises (SVEs)* [28] usable towards providing mgmt. and maintenance services (see Fig. 2).

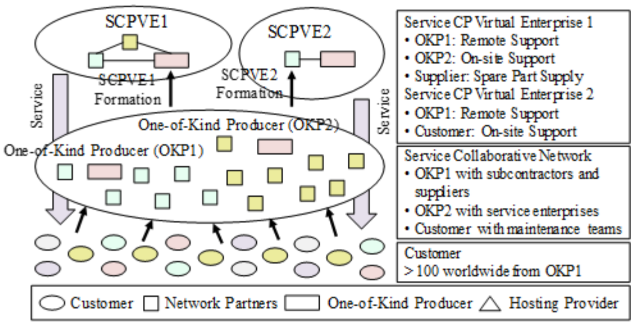

Fig. 2. Collaborative Service Model (based on [28])

The heterogeneous feature of construction projects has endured to this day. The advent of advanced ICTs, such as the Internet of Things, Services, and People (IoTSP), has prompted efforts to use it towards a new *Collaborative Networks 4.0* paradigm; however, as shown above, this is currently limited to a snapshot approach focused on the current technology. The proposed CNs approach, based on *Virtual Enterprises* [5] [28], has been proven in the industry in the past; moreover, when coupled with lifecycle reference frameworks it has been shown to also be able to support in a *holistic* and *integrated* manner the upcoming Industry 4.0 paradigm [27]. As such, it is highly likely to also be useful for the Construction 4.0 endeavours.

In the Industry 4.0 context, the CNs 4.0 can enable a group of smart enterprises to be selected from a pool of certified participants to promptly come together to form a *Virtual Cyber-Physical Enterprise (VCPE)* as shown in Fig. 2. This VCPE will employ agreed-upon standardized protocols and processes that can be digitalised and (partially or fully) executed by other CPSs. The VCPE can thus support an evolved CNs 4.0 paradigm addressing the heterogeneity problem of the Construction 4.0 paradigm.

The CNs concept makes the most sense when applied in a lifecycle context as one can understand how the various participants can interact depending on their current and future lifecycle phases. While there can be many ways one can model lifecycles of entities, intuitively the best way would be to choose a framework that integrates aspects deemed of importance to the project at hand in the context of participants' lifecycles. The *extent of digital maturity* appears to be the basis of the classification for any Industry, it, therefore, follows a framework that integrates this aspect in a lifecycle context that would be best suited.

Another important aspect is the distinction between management/control and the mission accomplishment (a product or service) of an entity. This allows to clearly define essential aspects such as organisational culture and *agility*, i.e. the capacity of an entity to adapt in response to changes in its environment to cope with them.

5.2 Enterprise Architecture Modelling in the Construction 4.0 Context

This paper will make use of the *GERA modelling framework* [6], depicted like a three-dimensional structure integrating several dimensions incl. those defined as important for the *Construction 4.0 paradigm.* For this paper, the authors shall use only a 'slice' (extract) of the modelling framework at the model level; moreover, the third dimension featuring aspects such as Function, Information, Resources, and Organization (FIRO), previously used in the paper will be flattened for the sake of clarity. The result is a modelling construct such as shown in Fig. 3. Of course, once the basic concept is agreed upon by the stakeholders, richer (and implicitly more complex) models can be created reintroducing additional aspects while preserving the lifecycle context, and the mgmt. vs. production viewpoint.

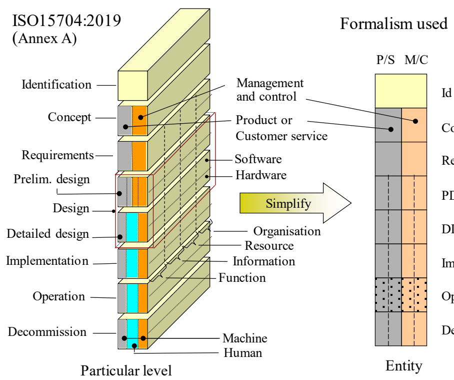

Fig. 3. GERA MF based construct (based on [6])

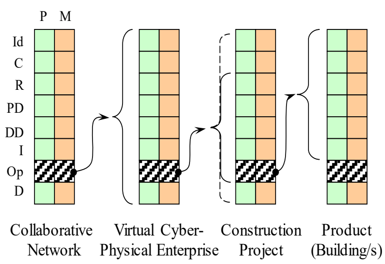

Fig. 4. Creation of the VCPE (based on [29])

Using the above-defined construct, one can model how the CNs concept can help the *Construction 4.0* endeavour. The modelling principle is shown in Fig. 4., whereby a CN composed of certified (qualified) suppliers creates a VCPE which then, in turn, creates (and typically also operates) a project whose purpose is to construct one or more buildings. The modelling construct allows depicting the creation and operation of Service VCPE for the maintenance of buildings, in the context of the lifecycles of all involved entities. Thus, Fig. 5 shows how several potential partners can agree (possibly at the initiative of the largest or most influential partner, the leading partners in the figure) to form a CN to be able to bid for and accomplish projects beyond their individual competencies.

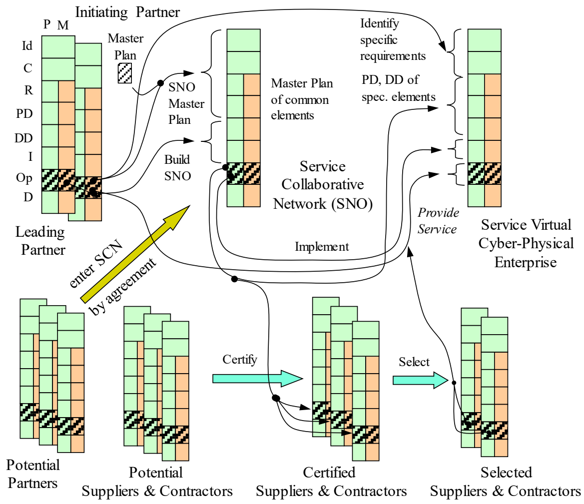

Fig. 5. Lifecycle-based Diagram for Building Maintenance (based on [29])

Thus, the Service Collaborative Network will be able, based on pre-agreed processes and protocols, to quickly form an entity having all the necessary competencies to bid for and accomplish a service (e.g., building maintenance) project. At the same time, potential suppliers and contractors will go through a certification process to achieve readiness to support an SVCPE as required.

As can be seen from Fig. 4. and Fig. 5, this kind of representation allows to detail de interactions between the most important participants in the context of their lifecycles while making the distinction between management and mission accomplishment for each entity. This is required to model a lifecycle-based solution that will endure in time, rather than a snapshot-type one that may only be valid for a limited amount of time.

6 Conclusions and Further Work

Achieving the *Construction 4.0* paradigm must overcome several hurdles specific to this domain; this paper has detailed some of them and proposed also some solutions. In the human area, the “Construction Worker 4.0” will be assisted by automation when and where required only. In the “Information Systems” area, adequate cloudification and interoperability standards have to be achieved. Lastly, heterogeneity of construction stakeholders present in a construction project setup and management has to be addressed. The paper has proposed the use of the proven *Collaborative Networks* paradigm applied within a construction lifecycle project to assist in the proper implementation of the Industry 4.0 paradigm based features in the construction industry. Further work will concentrate on the development of “enterprise reference models” for the *Construction 4.0* paradigm.

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