Integrating Industry 4.0 Associated Technologies into Automated and Traditional Construction

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Abstract –

Nowadays, it is ever more common to find mentions in the scientific literature to a "Construction 4.0". Considering, for instance, Offsite Construction, it is clearer how such concept could be realized. Current widespread adoption of BIM helps but is not enough to realize that end, because it is, in general, limited to information being manually created through authoring software, and consumed for different proposes, such as Clash Detection, or 4D Modeling. Construction 4.0 should transcend the limitations of existing only in cyberspace; it should interact directly with the real environment by means of sensors (gathering data), and remote controlled or autonomous machines, employed as part of the production processes, with Machine Learning algorithms handling the transformation of data into information, and actions. The central element of such approach should be a Digital Twin-driven Cyber-Physical System, which when focused on Construction Phase, would be capable to simulate the dynamics of construction processes. In this position article, an evolution of the concept of Computer-Integrated Construction (CIC) is presented as a possibility in representing and guiding developments associated to the incorporation of different technologies from Industry 4.0 to Construction. A framework where such a system could be applied to Off-site or Automated Construction scenario, and to Traditional Construction scenario as well is proposed. In the latter scenario, common in developing countries, which yet has plenty of (and need for) manual labor in the Construction sector, all those technologies are employed not to reduce jobs, but to augment awareness and eventually to turn the tasks safer for the worker.

Keywords –

Digital Twin; Building Information Modeling; Construction 4.0; Cyber-Physical Systems

1 Introduction

Some years ago, few people thought that the subject of a Fourth Industrial Revolution would be relevant to the Construction sector; one of the first researches to look for signs and directions of it on the industry, didn't found anything that helped towards this end [1]. Nowadays, it is ever more common to find mentions in the scientific literature to a "Construction 4.0", i.e., the application of Industry 4.0 associated technologies to the Construction (Figure 1). Yet, it is still not clear how all those technologies, Cyber-Physical Systems, Digital Twins, Industrial Internet or Internet of Things (IoT), to name just a few, will play a role to transform a sector that has been suffering to find its path towards industrialization.

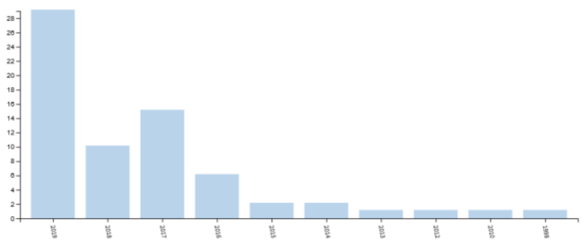

Figure 1. Publications whose subject deals with the concept of Construction 4.0, from Web of Science database.

Both the current importance that Computer-Aided Systems, including PLM (Product Lifecycle Management), has had in Manufacturing Industry [2] and the widespread adoption of its counterpart BIM in the Architecture, Engineering, and Construction (AEC) sector [3], helps but is not enough to realize that end. They are, in general, limited to information being manually created through authoring software, and consumed for different proposes (in case of BIM uses, Clash Detection, or 4D Modeling, for example).

Industry 4.0, as its own name states, is totally focused on manufacturing, i.e., production on a factory, or more specifically, on a factory with lots of automation that appeared during the Third Industrial Revolution. So, there is this necessity to traverse the cyberspace of digital models of the products towards the control of real machines, or of the entire factory, where happens the production processes.

Such trend aims at reducing time to market, enhance productivity, and achieve mass customization, among other goals. It is the integration of automation in the virtual world, and automation in the real world.

Considering "those aspects of the project that can be designed and managed, i.e., the product (typically a building or plant), the organization that will define, design, construct and operate it, and the process that the organization teams will follow" [4], and the "role of complementarity" that attest to the synergy among Product, Process and Organization [5] ("Manufacturing Technology" being part of the Process), the importance of abstractions or models of those aspects has been increasing. For the goal of a Construction 4.0, it needs a complete virtual or digital representation of the Product, Process and Organization, to be capable to integrate horizontally inside a company, and vertically through the entire supply chain.

Based on a literature review and cross-learning case studies between Manufacturing and Construction Industries [6][7], this position article adopts an evolution of the concept of Computer-Integrated Construction (CIC) as a possibility in representing and guiding developments associated to the incorporation of different technologies from Industry 4.0 to Construction. Industry 4.0, and its inspired Construction 4.0, should be about the integration of virtual and physical, and has in the technology of Digital Twin-driven Cyber-Physical System its most prominent technology.

Although the relevance of such technologies encompasses all the phases in the lifecycle of a building or infrastructure work, due to limited number of pages in that article, the presentation here restricts itself to the Construction Phase. Scenarios where such a framework could be applied to Off-site or Automated Construction in one extreme direction, and on Traditional Construction processes in the other (and the whole spectrum in between), are proposed.

2 Pre-Construction 4.0: Origins of Computer – Integrated Construction (CIC)

Development on Information and Communication Technology (ICT) systems could be traced back to the first hardware that enabled structural calculations, and software that enabled Computer-Aided Drafting systems. It was always done in parallel to innovation in Construction based on new materials, new technology in building systems, and new ways to manage construction processes.

The AEC sector being fragmented as it is, the same happens with its ICT software tools used by different disciplines and professionals. Many researchers were dedicated to the work of integrating the information of those workflows [8]. Construction 4.0 main idea is beyond integration inside virtual world, of the information throughout the lifecycle of the product, the building or infrastructure work: it is the integration of that information with the automation hardware on the shop floor, and the creation of new ways to operate inside an industrialized and automated environment.

There are some similarities between Industry 4.0 paradigm and a popular concept in the 80's, Computer-Integrated Manufacturing (CIM): both incorporate somehow the dynamics of the shop floor computer-based system, towards the goal of automation.

CIM was conceived as an integrated approach to end the 'islands of automation' around Computer-Aided Design (CAD), and Computer-Aided Manufacturing (CAM), and its communication with CNCs machines on the shop floor. The concept took advantage of a digital workflow of information about products and the automated production lines, with machines controlled by computers, and industrial robots: it should integrate and control the machines to produce based on digital information.

The adaptation of that concept to Construction was popular in the 90's, known by the term of Computer Integrated Construction (CIC) [9–11]. It seems that from the researchers inside this theme, there were two approaches:

1. **Focused on the integration between CAD and CAM**: or between design and fabrication – many advanced applications of that era were done without such integration [12]. In the search of that integration in the design phase, it seems also that researchers converged to create object-oriented data schemas and software tools, which in the end became to be known as BIM [13];
2. **Focused on the Digital Fabrication**: whose interest are on Off-site Construction, following assembly on site, and the use of robots and other automated machines – activities of Planning, and Monitoring were done based on digital models.

For the work presented in this article, the latter approach is more relevant. Following that approach leaded to Site Automation [14], Factory Automation System [15], Super Construction Factory [16], or similar approaches, to structure the unstructured onsite environment, so that it would be possible to integrate construction robots without disrupting other workflows around [5].

Such developments by all big Japanese Construction companies, such as Shimizu [17] and Obayashi [18], and replicated by companies of other countries, it should be viewed as a prototype of Construction 4.0, although many of the robots were by then teleoperated. To have a center of operations, and many different digital models, and the assembly of building components itself being done by robots and machines, it had all the elements that comprises the view of the application of Industry 4.0 technologies to Construction.

3 Industry 4.0 Associated Technologies

One way to understand the current drive towards a Construction 4.0 paradigm was presented in the previous section. Today, the maturity of different technologies that could be used in an integrated way allows the development of such future scenario.

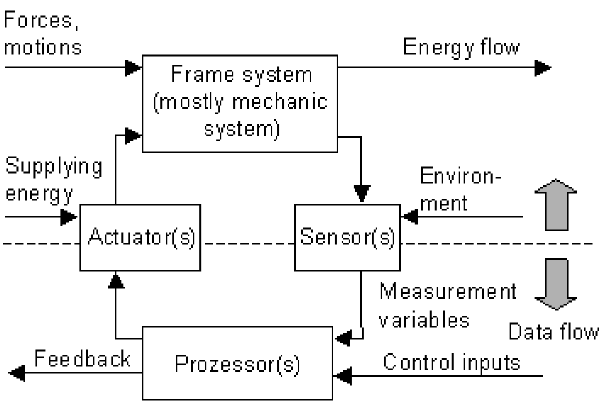

Figure 2. Representation of a mechatronic system [19]

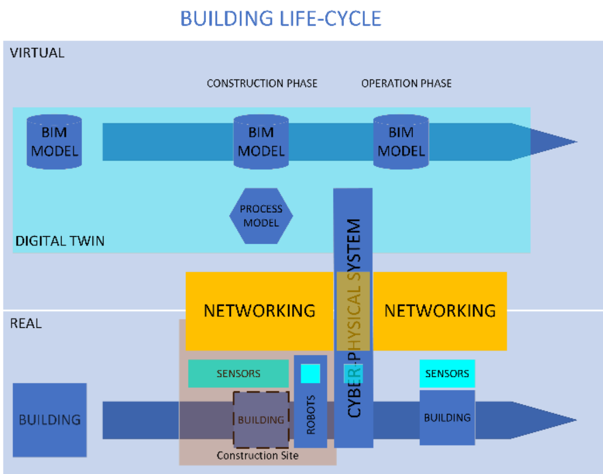

Figure 3. Diagram with the interaction between different Industry 4.0 technologies.

Thinking about construction production as a system, it is interesting to make an analogy with the representation of a mechatronic systems, as shown in Figure 2: 1) Sensor(s); 2) Processor(s); 3) Actuator(s).

Each technology associated to Industry 4.0 paradigm could be viewed as enabling sensing, actuation, and/or processing. The technologies that would be briefly addressed in this section are: Industrial Internet or Internet of Things (IoT), Digital Twins, Machine Learning / Artificial Intelligence Algorithms, and Cyber-Physical System.

Figure 3 illustrate how BIM models changes throughout in the building life cycle in the virtual environment, and its analogous, the physical building is being constructed and operated in the real environment. There is a networking layer that connects both environments, and the sensors that are vital to capture the dynamics of the construction site / shop floor, and the surroundings of robots and of cyber-physical systems, which by its own is driven by digital twins. The hexagon in the figure, bellow the BIM Model in the construction phase, represents the dynamics that are the simulation of the processes, and it enhances the product model, to provide some basis for a digital twin. With it, it is possible to create data and information beyond those produced by the professionals, automatically. In the operation phase, it is only possible to work, if buildings were designed and constructed with embedded sensors, or instrumentalized afterwards, to capture every relevant aspects of its uses.

3.1 Industrial Internet or Internet of Things (IoT)

IoT is about the convergence, where different devices (Things) are capable to communicate one with another over the Internet. They not only communicate; they sense their environment, and they could act over it based on programmed behavior. This “definition” could be stretched to encompass from sensor networks to autonomous systems, and certainly benefit from 5G networks, the existence of Cloud (Edge or Fog) computing nodes, and so on.

It should be the sensing layer, which is essential for whatever scenario of Construction 4.0 that is being proposed. The use of different sensors for tracking people, material, and equipment onsite, and RFID in modular plants could help to leverage the approach to Construction 4.0, producing database for construction processes.

The availability of computational power outside the local where data is collected, and even where it is consumed gives many more possibilities. It is more cost effective.

3.2 Data Analytics: Machine Learning (ML), Artificial Intelligence (AI)

Current successful approach to build complex models is based on data, with Machine Learning (ML) algorithms. It is possible to learn parameters of a parametric model, and to learn the very representation itself.

Machine Learning, or more generally Artificial Intelligence (AI) algorithms could also be used to analyze incoming data, to quantify uncertainty of different scenarios, to propose alternative solutions, and so on.

One necessity with the grow in sensors being used, and data being gathered would be infrastructure to deal with the Big Data Analytics. are analogous to what was presented in the previous sub-section. The differences are the hardware, software and workflow needed to do the same thing in a scalable manner.

3.3 Digital Twins

There is allusions to BIM being the Digital Twin version in the Construction sector, although with different names [20]. Following a PLM approach [2], some works also sees parallel between BIM and PLM. Digital Twins should, in an analogy to object-oriented modeling, provide not only the variables, but also functions pertinent to, and based on those variables. In the case of a building, it should incorporate physics to allow for showing its behavior with software running different simulations [21].

BIM models *per se* should not be considered Digital Twins when the focus of the analysis is the Construction Phase. All uses of BIM models [22] implies taking information from it, quantity takeoff, that generally were inputted by human, and need extra human work to integrate with other databases to achieve the desired result for such utilization – there is no transformation of the data.

So, BIM models, are considered the virtual representation of the Product. In such uses of the model for 4D Planning, 5D cost, it cannot be used *per se* to predict, and it doesn't have dynamic links to account for constant changes in design, planning or construction phases. Those models are created, in general, through human input through authoring software tools, one specific for each discipline, and that need to communicate through interoperable workflows.

Although there isn't general agreement around what BIM is and is not, a process, a 3D digital model of the product with non-geometric and geometric data, or a collection of authoring software tools, here it would follow some VDC practitioners that considers BIM as the digital model, and its uses as part of the VDC practice [4].

Digital Twin should incorporate in its representation functions to transform the initial information and producing result that do not depend only in data, but in inner behavior of the phenomenon modeled.

3.4 Cyber-Physical Systems

The term "Cyber-Physical System" was probably coined by Helen Gill at NSF around 2006 [23]. Figure 4 provides a concept map relating Cyber-Physical Systems to Feedback Systems and Real-Time [24].

Probably an evolution of Distributed Real-Time Embedded Systems (DRE), Cyber-Physical Systems are complex systems, which integrate in its design abstractions of control, system, and software engineering. It is inherently a model-based approach to provide interaction between the physical world and its dynamics, and the cyber or virtual world.

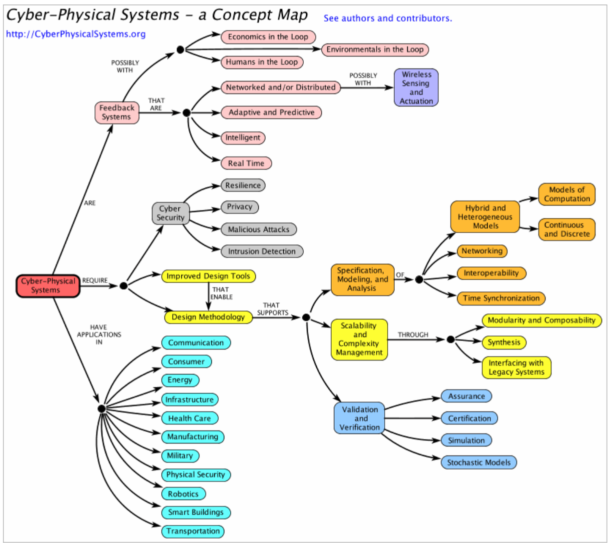

Figure 4. A concept map for Cyber-Physical Systems [24].

It could be driven by Digital Twins or work with other controllers: Additive manufacturing, and construction robots.

4 Construction in the 4.0 era

The challenges in creating a framework, which is valid over the entire spectrum of possibilities of different productions systems in Construction are:

- How to create a Digital Twin of the Manufacturing Technology, or the Virtual Representation of Production Processes;
- How it will behave, its inner dynamics.

It should be a software capable of simulate, at least, the construction process for each existent building system, allowing predictions in a closed-loop feedback, and possibly in real-time. It will depend on data from sensor networks deployed in production lines for offsite construction (where probably it will be Cyber-Physical System driven by Digital Twins), or on-site, for more traditional production or assembly of modular component.

For the case of the so-called Automated Construction, which we had the Sky-Factories or Site Automation as perfect examples, they already developed such supervisory and control system overseeing the automated processes.

But even for traditional construction in developing countries, that are prone to remain almost that way for the short future, such system could be implemented and used in such a way to give a better understanding to the people making decisions of an uncertainty-bounded possibilities for planning and rescheduling. The technologies adopted should promote the work of people, to make their time more productive, to make their work safer, and make their data-driven decision.

As presented in the previous section, a Digital Twin is the virtual representation of the Production process, when considered only Construction Phase. It represents how raw material and resources such as workers, machines, and so on, are transformed into building components, or the building itself, in such detail that it should be possible to predict the length of time needed to finished each step.

The simulation is the core engine of the proposed framework. Although realistic simulation models of the manufacturing of components in automated lines and considering the human interacting with machines already exist. It could provide scenarios with which to deal during planning, to re-planning during execution.

More challenging is the scenario of simulating traditional construction, in an unstructured environment, with lots of freedom to act. But here it is advocated that with a probabilistic model, constructed over a large collection of data, and individualized to capture each company way of work, could at least provide lower and upper bonds over variables such as cost, amount of human labor needed, alternative plans, risky, and so on.

Example of this approach was set out in [25], and a paper still not published, in which that framework was used over 5-years production data, and results are promising in capturing both the impact of the factory activities, and from panel design in the times in each workstation for wood-framing pre-fabricated homes.

There will be at first, two stages for that approach: 1) gathering data for different construction processes, to build a model or representation based on data [26], instead of expertise from professionals; 2) Application of that model, with real-time data still been gathered, to monitor processes, and to predict future scenarios, and plan in advance for alternative solutions.

Interesting for such approach, is the work that started with Occupancy Grids [27], then evolved to Metric Maps, and algorithms to build such representations at the same time that an autonomous robots navigate knows as SLAM (Simultaneous Localization and Mapping) [28]. Nowadays, SLAM has been used in Construction sector with point-cloud data to produce as-built and as-is BIM models.

It should be possible to decouple complexity on-site by modeling activities individually and allow a simulator for Discrete Event Simulation (DES) like Simphony [29], to add the complexity of interaction, and eventually, movement of resources. In the end, it could constitute a prototype of a library of Construction Processes, based on specific building systems, that could be tailored for each team or construction company, based on historic data of productivity.

5 Scenarios for the Construction 4.0

Two scenarios are being considered, based primarily in the availability of construction work force: 1) Industrialized Scenario, in which there is a lack of construction workers, and the availability of machines and/or construction robots directly responsible to the production process; 2) Traditional Construction Scenario, in which the sector employs a large workforce, but work conditions need to be improved by means of assistive technology.

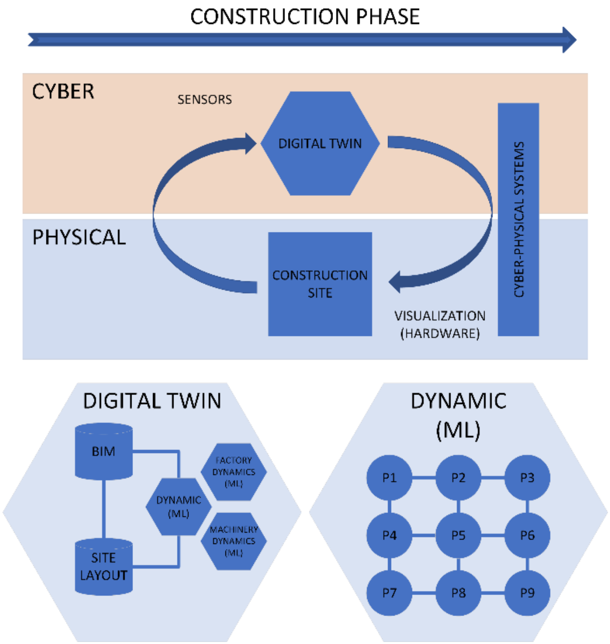

Figure 5. Scenario for Automated Construction.

5.1.1 Industrialized Construction Scenario

Modular, or Off-site Construction in general, could incorporate more straightforwardly Industry 4.0 technologies, although still there is many particularities that should be addressed. There is a large synergy between the different applications, although shop floor in the construction sector, be it for steel-framing, wood-framing, or concrete panels are not very much automated.

Figure 5 represent the industrialized scenario, where there is offsite production, automation in the factory, and eventually construction robots onsite. There are sensors gathering data, monitoring processes, and all data feed in Digital Twin model of the production processes. Those models produce actions to be taken by machines, or equipment which could directly made building components. The bridge between both environments, cyber and physical, is materialized by one or a hierarchical system of Cyber-Physical Systems (CPS), which allows a bidirectional link between BIM model inside the Digital Twin, and the real environment by means of "autonomous" machines.

The more automated the production, the less is the uncertainty, and the final difference between predicted and measured metrics in production. The dynamics would be made of an array, or lattice of production models, with varied dependencies among them, allowing for Machine Learning reasoning.

5.1.2 Traditional Construction Scenario

The main difference between both scenarios is the Cyber-Physical Systems, which are absent in the traditional construction scenario. Moreover, the framework for traditional construction works with human-in-the-loop simulations, as there is not a bidirectional flow of sensor readings and actuation controls between virtual and real environments.

There are countries, mainly developing countries such as Brazil, where there is a real concern regarding substitute Construction workers by robots or machines. Also, workers of the sector receive low wages, and they work in conditions that are potentially dangerous, and hard [30]. For that matter, where there is plenty of (and need for) manual labor in the Construction sector, all those technologies, and the scenario for a Construction 4.0 should be employed to augment and to turn the tasks safer, for the worker.

So, there is an opportunity to change current culture in the sector in those countries, an promote an environment of continuous learning, and to provide better jobs for such individuals by means of using assistive technologies [31][32]. From electric or electronic tools, exoskeletons [33] to facilitate tasks and avoid injuries, tracking systems to manage safety, and so on.

When such approach is deployed integrated with its virtual counterpart to coordinate efforts, to plan and control in a micro-management, it should produce better results.

There are many challenges in this scenario: 1) as it needs more human labor, it increases the number of sensors needed to capture activities on-site – although one could use imaging techniques; 2) the trajectories or the movement of the workforce should allow the identification, at least, of the beginning and the end of each activity in the sequence for the entire production onsite; 3) Those indirect detections could allow the estimation of work complete, and also constitute in historic measurement of productivity; 4) Using Machine Learning algorithms over such databases, it would be possible to incorporate uncertainties in the simulation, and provide worst- and best-scenarios for the planning with human-in-the-loop.

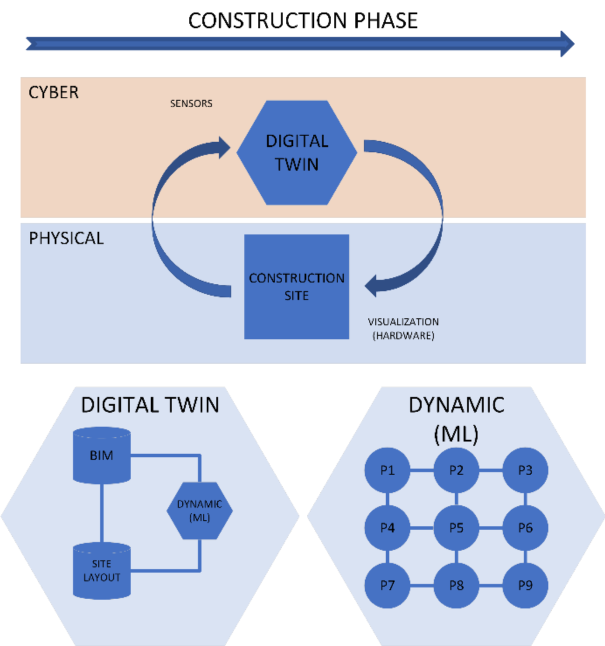

Figure 6. Scenario for Traditional Construction.

It is known that only technology changes would not make a case without addressing how to finance, how to bid public contracts and how to turn it competitive in terms of taxes.

6 Conclusion

In conclusion, a possible Construction 4.0, with two different scenarios that encompasses both Industrialized and Traditional Construction was presented. There should be a large spectrum of applications, in which the assimilation of the different technologies associated to

Industry 4.0 would differ.

As it is based on the digitization process, and its most important piece is the Digital Twin of the Production processes, it is essential that there is a widespread use of sensors to provide real data, and also almost real-time information of the processes, and that planning and control onsite be made in a data-driven approach.

It emphasizes that Construction 4.0 should be a holistic view, to provide a starting point to think about the future of Construction in considering Sustainability, in becoming part of a Circular Economy, and to an approach that considers society and the needs its work force in each different country.

Construction 4.0 won't be relevant without new forms of management and control, that should be proposed to incorporate as a base for a support system a micro-management, with automatic acquisition, and processing of data for the decision-making support system. However, such topic was outside the scope of this article.

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