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A Theoretical Framework to Align Lean Construction Techniques in the 4.0 Building Industry

KEYWORDS: Building Process Management, Lean Construction, 4.0 Industry, BIM, Agent-Based Modeling

The big challenge of the current industrialized society is the concrete adoption of 4.0 paradigm: this consists in the interconnection of the physical object to digital computation, by a collaborative and dynamic approach (i.e. Internet of Things – IoT). The creation of this interconnected computational network allows verifying the efficiency of a production system by recursive checks, which locates lacks and misproductions into the production chain. The progressive improvement of production quality, intended as the approach of needs and performances, is the core of Lean paradigm. In the big picture, these are the fundamental elements needed in the current condition of the Building process, that has an evident delay in technology and management techniques adoption. As an answer to this need, the research is oriented towards the definition of appropriate methodologies useful to seize the opportunities that the paradigm of 4.0 industry offers to the building sector in a lean way: the goal is, on the basis of literature review and tests on techniques and tool currently used, to outline a methodology that, using the continuous exchange among physical devices, data-processing centres and vice versa, can give new spaces of application to Lean methodologies in the construction sector. Considering the complexity of the Construction Process, even for small and medium projects, it is necessary to design on collaborative digital platforms, such as Building Information Modeling - BIM: in this research, the BIM model is the starting point by means of a quite-reliable database of properties and geometries of the building. On the other hand, all the problems related to the 'BIM Utopia' are investigated, such as the limits of interoperability, the slow adaptation of the construction chain to the procedures of good practice and the use of digital tools, as well as market fragmentation, which is very marked in culturally 'handcrafted' contexts, such as the Italian one. This research describes, basing on the test conducted on the existing methodologies, a theoretical framework to align Lean Construction techniques in the 4.0 building industry. The results show how is important, to reach the goal of optimization – the core-mission of Lean and 4.0 – move beyond BIM, in the direction of implementing existent methodologies and tools with Artificial Intelligence techniques, like Agent-based simulation. In the proposed framework, this is possible thanks to the improving of BIM capabilities with Autonomous Agents. They are modeled according to BIM object feature but including also relational rules and goals. So, after the definition of needs and requirements of design and construction process they tend, after ever modification occurred in the design environment, to create a new state of balance, defined by reciprocal satisfaction of boundary conditions: in summary, the Agents simulation allow to define, after every project modification, the satisficing balance condition respecting to all constraint that characterizes the project. This could properly support the designers in problem-solving, manage the huge mass of data that characterize the building industry and preserve the quality of the architectural design.

INTRODUCTION

This research focuses on the investigation of the new possibilities given by the development of Information and Communication Technologies - ICT to manage Building processes, with the ambition of grasping which vision is more appropriate to the spirit of our time.
In this field is clear that innovations in the ICT sector should not be seen as a parallel path with respect to the social and cultural debate related to architecture, but it is necessary that the different instances influence each other, as happened for the study of lights in the masterpieces of Caravaggio, the perspective in those of Piero della Francesca or in the implementation of digital tools of geometric modeling implemented by Gehry (Pascual, 1998).
It is therefore clear that, in addition to the increase of the performances of technological tools, it is necessary to adapt tools, methodologies, knowledge and the vision of a sector that, otherwise, risks losing the opportunity that the galloping development of the digital world offers; otherwise, the same development requires a constant updating of the results achieved, thus avoiding the risk of losing dominant positions and become, in a short time, obsolete compared to the needs of the industrial sector.
Hence, the target is in linking the information model of the digital building (in terms of Information Modeling) into an environment-mirror modelled by autonomous intelligent entities (Autonomous Agent). The prediction produced by these real construction process, in virtual-digital environment could, furthermore, be improved with the connection with new tools that, concretely, defines new paradigm in construction sector. These are the encompassed in 4.0 industry, in terms of connecting human resources with machines, also in terms of improving the data-exchange among actors (i. e. mixed reality devices for sharing knowledge directly on site, or wearable technology provided by RFID to warn workers about risky areas or activity etc.) In other words, the improvement of tool opens the way to a better human-machine interaction, capable to grow up the productivity and the global quality of building design in our digital era that, in reality, allow to extend the industrial concept of mass customization also in construction that, traditionally, is heavy conditioned by traditional approaches.

BACKGROUND: THE BROADENING OF INNOVATIVE HORIZONS

From the very beginning, the Building Process actors have found in Computer Science a valid partner, able to effectively manage important amounts of data and equip, in an ever more democratic way, the Construction Process actors with tools that are sufficiently complex, with respect to the insidious complexity of the design problem (Kunz & Rittel, 1970). These tools have gradually evolved, depending on the available computing power, allowing at first the possibility to manage geometries and data in separate environments and, from the last decades, modeling information and knowledge in interconnected holistic environments, such as happens in the BIM approach.
In most of industrial sectors, the opportunities provided by the digital revolution have been applied from the outset, with all the limitations and problems linked to the immaturity of these systems.
If we consider that we are still in the pioneering phase of the digital revolution, we can say that the results have been, at least, encouraging.
Differently, the Construction Sector suffers of a traditional reluctance towards innovation: the design procedures of wide use, in fact, still show several shortcomings, such as the low use of Information Modeling or (so?) the fragmentation of knowledge, continuing to work according to the logic of 'watertight compartments' consisting of design teams that, each for its own competence, store their methods and results in 'mental silos' (Clausing, 1994). Thus, the project is divided in specialized phases, to be verified in a consequential-linear way: this implies the presence of many parallel partial and sectorial projects, verified only within their own knowledge domain.
So, their contents and concepts are not integrated with each other, despite the complete use of advanced tools based on Computer Aided Architectural Design - CAAD. Therefore, despite the well-known potential of CAAD system in realizing a collaborative design approach, these are not adequately used in an integrated design vision (Carrara et Fioravanti, 2001), supported by digital networks: the problem, hence, is not totally connected with tools or the related digital environment, but in the need of a new approach, based on the new view about Building Process Management in a digital/collaborative way.
In this sense, the construction sector cannot miss the opportunity given by the paradigm of industry 4.0 in improving the connectivity of objects among themselves and between operators: thanks to the Internet of things, it is possible to increase the use of sensors in the operational phase of the building, to analyse the evolution of the needs and preferences of users; then, in the construction phases, it can connect the physicality of building site to the digital environment, necessary to control the quality of materials, construction and installation of systems and the overall performance intended as the achievement of the objectives set in the planning phase.
Other interesting perspectives openings towards the Facility Management, were the cybernetic connection among building object and management tools, allow to verify the operational response that the solutions designed give to the needs of users, and all the necessary materials and interventions needed from the building during following years.
In this reciprocal exchange of data and knowledge, human intelligence is flanked by Artificial Intelligence to better express, thanks to the possibility of having predictive tools with respect to the choices made, a strategic vision for process management.
In the building construction process - dominated by uncertainty - these possibilities open up unprecedented scenarios, with regard to the possibility of efficiently optimize Building Processes in terms of design support systems improvement, the reduction of effective time and cost of construction, a reliable forecasting in the maintenance and management of the real estate assets.

INTRODUCING LEAN VISION IN THE DIGITALISATION OF A/E/C SECTOR

The management techniques of complex project have now been extensively tested and catalogued, according to various categories - both operational and logical - that have been consolidated for years. Starting from the rationalist-scientist position of the late nineteenth century, first formalized by Rankine (Koskela et al, 2017) and then refined and propagated by the Taylorist school, the typical reasoning of engineering was framed according to the deductive method (from postulate to theorem). This is particularly evident in purely-analytical approaches: given the characteristics of an element and established the relative boundary conditions, the prevailing behaviours arise.
On the other hand, the inductive approach is based on the critical observation of the real world, in order to extrapolate its empirical knowledge, and then formalize it in rules of good practice; from here it is possible to conceptually 'induce', adapting the knowledge base acquired to the specific case. These adaptation processes, guided by the technician's experience and his ability to address a strategic vision to the solution of the problem, therefore allow to reach the satisficing state (Simon and Simon, 1962) with respect to the results to be achieved.
In the Building Process Management these two approaches have been declined according to the methodologies push and pull: the first one, is based on the push of production chain on the

basis of the starting conditions; the second one instead, is pulled according to the conditions and the adjustments needed at each time, basing itself therefore on the observation of the real world and on the forecast of how the process can be adapted to the dynamic project/building conditions.
In the peculiarity of the construction sector, the management of push-based production was applied through the Critical Path Method - CPM in the 1960s, with a clearly rationalist imprint (Koskela et al. 2014). In applying this method, the reference to be followed is only the ideal conditions assumed for the production line, leaving the minimum space for the complex variables given by the real world which, instead, in such a dynamic context as the construction site, become decisive for obtaining the result.
In searching of optimisation methods for the construction sector, the application of techniques developed in the field of vehicle manufacturing (i.e. the lean manufacturing approach), has been a long way forward. This consists in optimizing the use of available resources in a process, minimizing wasted time, under-utilisation of work areas and resources and, in a broader sense, misproductions. These are the inefficiencies that, in fact, bring useless costs and inefficiencies so that each project systematically becomes a race to the unknown.
Therefore, the necessary integrated approach to project management allows not only a change in the operating and management methods of an architectural implementation process, but also a different cognitive approach capable of bringing the competences of the actors closer with the aim of reaching a satisfactory condition, with respect to the project requirements, and arrive at the best possible solution in a shared way (Froese, 2010).
In this context, it is necessary to provide to process actors 'aggregators' capable of always keeping the project variables in connection and, therefore, the creation of a digital knowledge formalized in an explicit way, cataloguing elements used in previous processes and, above all, their relationships. This condition, in these years, seems more and more within reach (fig. 1).

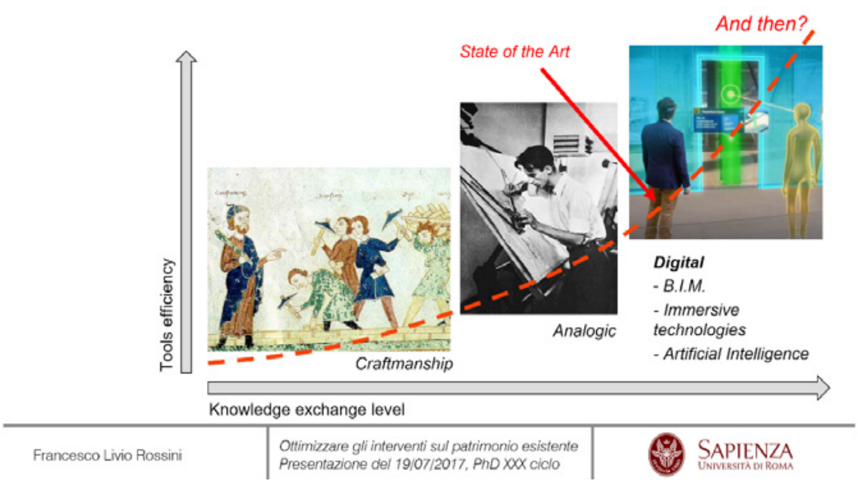

Figure 1: evolution of production efficiency in Building Design Process

DIGITAL TRANSITIONS IN BUILDING CONSTRUCTION MANAGEMENT: A DIFFICULT PATH

Unlike the first wave of CAAD, where the lower diffusion of tools and data-networks overshadowed the problem of design collaboration, in the second phase, between the 80's and 90's, the widespread presence of digital tools and the progressive construction of the necessary digital infrastructure, determined the possibility to finally share collaborative platforms and increase the quality of work through continuous and reciprocal exchange of knowledge, although not fully formalized.
Now, in the middle of the third wave, characterized instead by the adoption of highly effective technologies in the exact definition of a building component and objects in general such as Building Information Modeling - BIM and by interoperability platforms such as the Industry Foundation Classes - IFC, the digital construction of the project is achieved (Fischer et Kunz, 2004). In this direction, research lines about interoperability are achieving important results, as described by Daniotti et al. (2017) in defining digital platform of interoperability. But, according to Miettinen and Paavola (2014) the BIM is still an 'utopia', a promising technology that have to be still implemented to manage properly the complexity of the Building Process.
Therefore, the challenge consists in going beyond the current potential through collaboration, understood as the management of the flow of information and knowledge between the actors, aiming at the mutual increase in governing design problems, and the possibility to interact with simulative models, capable of foreshadowing the realization and the behaviour of the project.
The advantage is therefore in being able to verify in advance both the design solutions and the construction possibilities, in a continuous evolution of the digital project.
In this way, thanks to the advances in digital simulation, with which it is possible to define choices and their consequences, it is possible to optimize the use of resources involved (i.e. workers, spaces, materials etc.) reducing the typical risks of construction like variations in progress, with the known repercussions both in terms of time and cost, both on the overall quality of the process of construction of the architecture (fig. 2)

Figure 2: example of propagation of Project Construction cost and time and the related incoherency between the final result (on the left) and the initial project. Rome Convention Center.

METHODOLOGY: IMPLEMENTATION OF BIM WITH AGENT-BASED SIMULATION

In the current literature is extensively documented how the digitalization of Building Process could bring benefits in terms of optimization of resources involved in the Construction sector. On the other hand, the limits of the most promising methodology in this field - the BIM - , are well known: interoperability, generation gap, digital divide etc. Now, the interest of the research debate about design methodologies is moving from digitalization of process to the spreading of computational into the real life through IoT, AR/VR/MR etc.
So, digital model of building has to be interconnected with the physical environment with devices that, for instance, are installed in site to gather data like occupancy, progression of works, prevalent behaviour of workers (or occupant in case of evaluation studies of usability of buildings) and so on. Furthermore, designers have the need to manage a very complex amount of data, that requires the evolution of this tools from a reactive behaviour to the proactive one (Fioravanti et al., 2017).
This means that a modeling tool does not merely act basing on designer instructions but providing him in advance choices that have a high probability to be the more satisficing to the project needs. To reach this achievement an Agent-based simulation model that integrates BIM capability is proposed: in summary, this simulation environment sense the needs and the resources modelled into the BIM environment and, via recursive simulation, predict the best use of design object available in the model in respect of the needs to be satisfied.
These agents are characterized by a set of rules to be respected, related goals to be achieved and, in relation to these, set mutual relationship that defines the way in which, by applying their inner systems of rules, Agents modifies their internal balance. This process happen hundreds of times till the definition the best way to pass from the starting condition (Contest at time-0) to the defined next step (Contest time-1). If the simulation take place into the BIM model, sensor and actuator of agents act into values of digital model, if the agents are connected to the real environment – e.g. Facility Management, Digital Fabrication etc. – sensors are physically connected to the real environment, then actuator (i.e. mechanical systems) after computational inference, modifies real object, materialising the digital continuum that is the core of 4.0 (fig. 3).

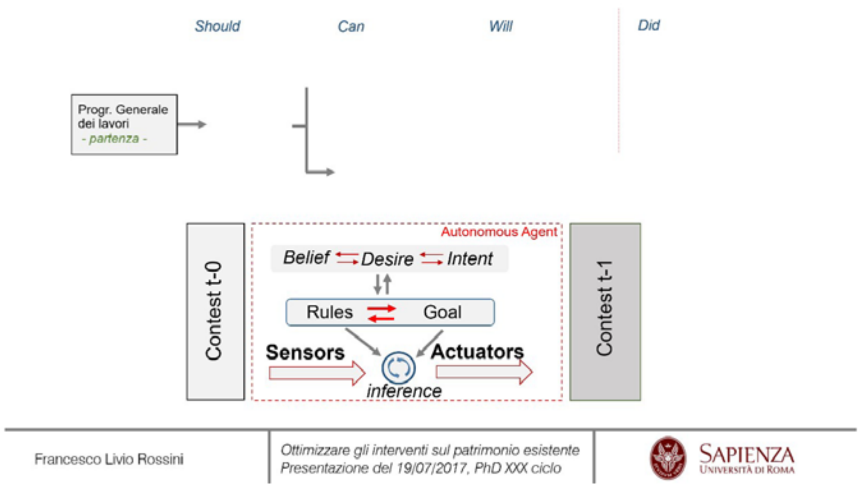

Figure 3: the inner conceptual structure of Autonomous Agent.

Agents are autonomous: autonomy, in fact, means the ability of an agent to act, after perceiving a stimulus, by applying rules aimed at achieving an objective without direct human control. This autonomy can be declined according to different levels of complexity. In fact, an Agent can have very simple behaviours, purely reactive with respect to the application of conditional rules of the if-then type, towards more complex realities such as the Belief-Desire-Intent-BDI architecture. In this case: the Belief is generally defined as the information that an agent has with respect to his environment, which can be more or less accurate, depending on the type and precision of the sensor used; the Desire instead describes one or more objectives that an agent would like to see concluded, with the definition of priority rankings; the Intent is the way in which Agent tries to intervene on the current state, both within his system and in the environment in which he is immersed.
Agents in this case represent the elements edited in the model, and the external components that influence these building elements; these are the context, understood as the organization of the
construction site resulting from the iterative feasibility checks and the resources to be employed, defined in turn according to the tasks and the degree of productivity that they can achieve.
In this way, the Lean approach is applied in the way in which this intelligent digital system is able to optimize the resources involved in processes. This became possible when the system is:

- **able to optimize the project** in terms of reduction of hard/soft clashes, the possibility of project-inconsistencies, and related reworking activities, and/or reducing the redundant solution (mostly in HVAC design) and, finally, improving the usability of architectural spaces by users in operational phase;
- **able to optimize the construction management**, in terms of a better management of working area through the use of Line of Balance – LOB Project management approach, in a construction site planned with the Location-based Systems – LBS (Rossini et al, 2016);
- **able to minimize** the interruption of building use, warranting the service provided by the building, thanks to the reliable definition of time and space occupation given by digital simulation of construction and construction site development during the whole cycle of works.

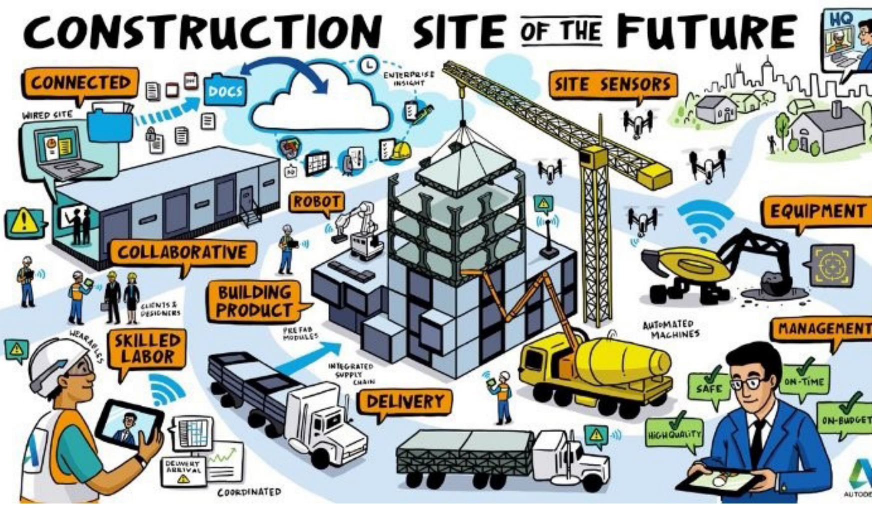

Figure 4: the 4.0 construction site. Thanks to the wide use of sensors, digital dynamic models of building and improved human-machines interfaces, is possible to manage collaboratively the Building process, in a safer way. From LinkedIn, J. Gall, 2016

CONCLUSIONS AND DISCUSSION

This research is included in a broader project, that has the goal to formalize a design digital environment for the co-creation between humans and machines. In this way, it becomes easier and more reliable to make, in earlier project phases, accurate assessments of the feasibility of projects, with the goal to save resources and safeguard the – often weakened – design quality.
Considering the aspects related to Agent modelling, we have not yet structured knowledge bases or 'well-defined' knowledge structures, based on scientific observation of performances of construction sector, or extracted from large databases: therefore, especially in the definition of the productivity of the operating teams, one must still rely on the implicit knowledge of the actors involved, the Expert.
The opinion of the Expert is therefore altered by the influence of (his) bias or evaluations that are simply based on performance that cannot be objectively verified.
Although such a simulative system could prefigure scenarios that are certainly valid from a logic/informatics point of view, they are based on a subjective knowledge base, which is therefore characterized more by the implicit knowledge of the Expert than by the objective observation of the phenomenon. In further researches, the focus will be targeted on the data gathering in the construction process, using advanced techniques like Big Data.

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