

Article

BIM-LEAN as a Methodology to Save Execution Costs in Building Construction—An Experience under the Spanish Framework

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Abstract: Current market conditions characterized by technological changes, increasing regulatory requirements and low funding make current construction management models obsolete. This tendency affects not only the private housing market but also public administration projects, which have large time and budget deviations across the board. As a result, new approaches are needed to improve the efficiency of the construction process, removing extra costs and delivering projects on time. The most representative trends in the construction industry that enable such improvements are both Building Information Modelling paradigm (BIM) and Lean Construction philosophy with one of its associated tools in the field of construction management—the Last Planner System. However, a review of the literature shows the scarcity of works on the synergy of both paradigms taking into account the extensive literature on Lean and BIM individually. This is further accused if we look beyond the theoretical literature reviews. Therefore, this paper is focused on the benefits derived from the synergy of both disciplines and the impacts on project efficiency through a case study of a public construction project at the university of Alicante in order to provide empirical evidence of the benefits and improvements of using BIM at the Look Ahead meetings and of the Last Planner System. Finally, the results of the case study allow us to make a comparison with the data related to cost deviations of other public projects with different uses, built areas, and complexity which were managed with traditional methods of construction.

Keywords: BIM; construction clashes; Last Planner System; Building Information Modelling; Lean Construction

1. Introduction

During the so-called real estate bubble, the construction sector in Spain experienced uncontrolled growth, both at a private and public level. This progression led to private housing prices reaching excessive levels. This lack of control also extended to the public administration, which tendered for projects that were developed with little control and large detours. This predisposition for considerable time and cost deviations during the execution of construction work, was one of the main causes of the real estate bubble burst. The problem related to cost overruns and deviations in building delivery times also extends to the international context, where some authors identify an average cost overrun of 12.22% in construction and engineering projects [1,2]. Some authors state that only less than 25% of the projects awarded in public bids remain within 10% of their contractual deadlines [3]. Several factors that favour the appearance of these deviations have been identified during the present research. They have been classified given their root cause according to human, technological causes, political reasons, or other causes derived from

the intrinsic complexity and variability of the construction projects. Human causes are fundamentally associated with the limited communication that exists in a generalized way between all the agents that participate in the development of the construction project. This limited communication usually comes from the competitive atmosphere resulting from the diversity of participants within the same construction company, as well as the diversity of subcontracted companies [4]. Also, the competitive environment encourages the tightness of information so that information does not flow to all participants, or does not do so in time, creating bottlenecks, unnecessary work and rework [5]. Some authors established that up to 30% of construction activities are rework tasks [6], that is, redoing a process or activity that was initially poorly performed, and the demolition of units that were previously poorly executed affecting both cost and delivery time [7–9]. Between 6% and 12% of construction cost overruns originate in the re-construction of poorly executed units detected once the unit has been completed [10,11], and this is further aggravated by the general lack of motivation of the construction company crews and subcontractors [12]. An additional factor reinforces the problem of human error, and is the low adoption of technology in the sector, which continues depending on human people in both artisanal production and management, rather than on automated processes. This technological gap contributes to the inefficient performance and lack of transparency of the process, resulting in duplication or absence of information, and erroneous or questionable information [13]. Finally, there are some variables that affect project performance which exist in all construction projects due to their complex, uncertain and variable nature [14]. These causes, which are inherent to all construction projects, include delays in the delivery of material and equipment orders, design errors, changes in design, breakdowns and malfunctions of equipment and auxiliary resources, absences from work, greater environmental impact, more work-related injuries and other aspects that affect productivity ratios [15]. These changes in productivity ratios produce deviations from the initial project plan, and encourage improvised decision-making instead of meditated and controlled decisions. Finally, the literature also includes causes of political origin. In general, low levels of control during the contracting and construction of projects have been identified as an alarming issue for researchers and any interested agent in the sector, who claim a change in regulation to avoid reckless contracting, since according to the literature there is a correlation between these irresponsible bids and budgetary deviations during construction [16]. Specifically, in Spain, actions are being undertaken in both the public and private initiatives, such as the report by the Spanish Confederation of Business Organisations which proposes to improve the legal framework and contractual procedures for contracting construction companies. Actions have also been promoted from the public administration such as the publication of a new procurement law for the public sector which aims to provide greater transparency in public tendering processes and to define actions for greater control of the construction process. Furthermore, other measures have been introduced to digitize the construction process, following the European trend that has been establishing the use of Business Information Modelling (BIM) in recent years [17]. As a result of the foregoing, a rethinking of the practices and procedures used until now is necessarily needed, being unavoidable the definition of new guide lines of action for greater efficiency in construction projects (Figure 1).

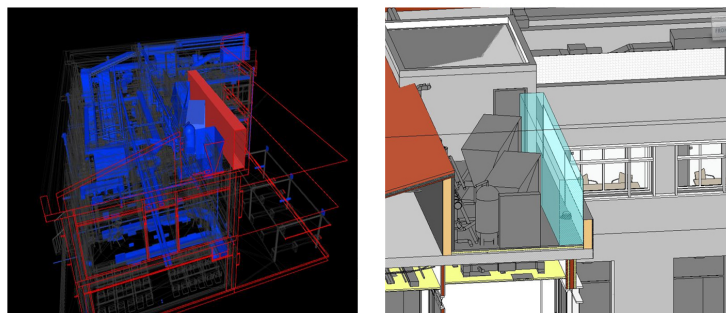


Figure 1. Example of problems detected in the previous phase of a construction project.

For all the above reasons, this paper focuses on the incorporation of actions that allow the improvement of performance during the construction phase, minimizing deviations from what was planned. In accordance with the above, the following sections examine the application of the most relevant current trends on the sector in order to improve performance during the construction process. Currently, the most studied approaches in the area are the Building Information Modelling (hereinafter BIM) and the Lean Construction paradigm. The tools associated with BIM represent the emerging technology that allows construction projects to be managed centrally throughout their life cycle, from the definition of the preliminary project to the end of its useful life, concentrating all the project information in a digital information model accessible to all participants [18]. Another growing paradigm within the construction industry is the Lean Construction philosophy. Lean Construction is an adaptation of the Lean Manufacturing philosophy to construction, with the aim of improving performance by reducing waste, that is, processes that consume resources and do not add value, while maximizing value [19–22]. Some of the most common waste are errors that require rectification or rework, unnecessary movements of material and workers, underutilized material and resources, and bottlenecks due to delays. One of the most representative tools of the Lean Construction philosophy is the Last Planner System, which allows agile and proactive management of construction projects through collaborative planning involving all stakeholders [23]. However, during the development of the present research the authors identified a gap between the number of studies of these emerging paradigms at an individual level and their joint application in indexed journals. Also, the literature review shows the need to provide data beyond the theoretical scope in these indexed journals, to demonstrate the viability and to validate the integration of both paradigms during all the chapters of the construction phase.

Therefore, this paper studies the benefits of the application of both paradigms together, the impact on project efficiency, and the feedback and support of both paradigms. In order to validate the feasibility of implementation and the synergy of both approaches, a case study of a public construction project is presented. The case study has allowed authors to obtain results draw conclusions and give empirical evidence to the theoretical studies of scientific literature. In addition, the results obtained have allowed a subsequent comparison of results with other public construction projects managed in a traditional way. To this end, this paper is structured as follows: in the following Section 2 we describe the BIM paradigm and the Last Planner System as the most representative approaches currently applied in the construction sector and the literature review on the synergies of their mutual application. In Section 3, the research approach is presented. In Section 4, the main contributions obtained in the case study are developed to demonstrate the feasibility of the joint implementation and to validate the synergy, through the analysis of the benefits and improvements derived from the use of BIM tools during the Look Ahead phase of the LPS system in the construction phase of an extension of a public building, the Multipurpose Building III at The University of Alicante. In Section 5 we present a comparative analysis with the data related to time and cost deviations of other public projects which were managed with traditional methods of construction, as well as the research findings and discussion. Finally, in Section 6, the conclusions of this paper are presented.

2. Current Approaches to Optimize the Efficiency of Construction Projects

2.1. Last Planner System

The Lean Construction philosophy allows the management of construction projects through the reduction of cycle times and the simplification and minimization of the necessary processes to undertake an activity. This is achieved by increasing production flexibility and transparency throughout the process, through tools that allow global control of the process, reducing variability and establishing continuous improvement. One of the most representative tools of the Lean Construction philosophy is the Last Planner System. This tool allows an agile and proactive management during construction work, moving away from some traditional project management methods, such as the critical path method that only allows a late detection of deviations.

In addition, these traditional methods are generally unrealistic with respect to the reality of what is actually executed, being simple expectations that are corrected during the execution of the work, simply adjusting to the deviations [24], and in many cases re-planning is abandoned. This because interconnections between environmental variables and factors that may influence project development are not linear relationships as traditional methods suggest, but are in fact complex relationships of causality and effect [25]. Given this gap, the Last Planner System offers the possibility of generating a realistic workflow based on a collaborative planning which is developed by all the agents involved, where the acquisition of commitments and the agility of replanning allows to face changes and unforeseen events that may arise during the development of construction work (Figure 2).

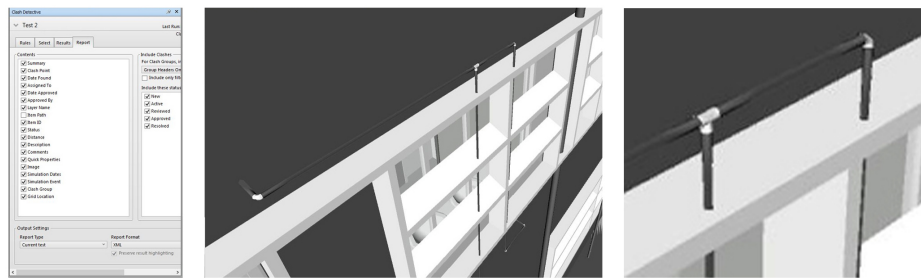


Figure 2. Intersection conflicts through the coordination of the construction project.

All this confirms the capacity and suitability of the Last Planner System for the management of construction projects, and its variable and complex environment, since it provides versatility and agility. This agile management ensures better performance by minimizing variability, while providing reliability to work flow through commitments and mature decision making. This is achieved through the different phases of the Last Planner System that extend in different time horizons throughout the construction project: Master schedule, Phase Scheduling or Pull schedule, Look Ahead Planning and Weekly Work Plan. The system begins with an initial meeting where milestones and deadlines from the Master Schedule are established [26]. This phase known as Phase Scheduling or Pull Schedule as a result of the use of the Pull system to carry out a collaborative schedule of activities among all stakeholders, starting from the milestones or completion date from the end to the beginning, that is, in reverse to the date of termination [27]. This Phase Scheduling precedes the Look Ahead Planning phase, that links long-term planning with short-term commitments [28], at this point workflows of each activity in that period are identified, usually from 4 to 6 weeks in advance. Then, an analysis of the restrictions that may affect both the start and the development of planned work is performed, classifying them and establishing a responsible person and a date for their solution before the start of work. Then, restriction-free activities go to the next phase, the weekly schedule known as Weekly Work Plan, which is the most detailed planning before the start of work. Finally, performance is assessed through performance indicators called Percent Plan Complete (hereinafter PPC) which allows comparing planned activities with those executed.

2.2. Building Information Modelling Paradigm

Nowadays, the use of BIM enables an integrated solution for managing construction projects throughout their life cycle. It is the emerging technology standard that provides improved construction data management. This information, acquired during the entire life cycle, is integrated into a single model that acts as a repository for all the information accessible by the agents involved. In relation to its implementation, national public administrations are preparing for its adoption especially after the European Directive for Public Procurement, which demands the use of BIM in construction projects financed by EU public funds. But although some countries like The United Kingdom, Denmark, Netherlands, Norway and Finland already require BIM for public projects, there are other countries, such as Spain, where the awareness and the adoption among construction stakeholders is currently

spreading [29], and the implementation has not started for the administration and is still at an initial stage above all for SMEs.

Several works on BIM implementation have been found during the literature review. Other works identify and validate BIM benefits during both the design and construction phases, through visualization [30–34]. These visualizations allow the identification of conflicts before they occur, and this concludes in savings of up to 10% of the budget value [35,36], reducing document omissions by up to 52%, up to 48% of reworks, and up to 39%, of time reduction in the accomplishment of construction works [37,38]. Benefits related to cost reduction and control throughout the project life cycle are noteworthy [39,40], since BIM provides predictable information with regard to quantity, cost, schedules, and materials. In addition, BIM creates and makes available early information, and ubiquitously facilitates access to site information at any time and from any location, thus bridging the gap between information availability and response times. In addition, the BIM facilitates the flow of information and increases the transparency of the whole process, integrating best practices and knowledge sharing from one project to another, thus promoting continuous improvement [41].

2.3. Synergies between the BIM and LEAN Paradigms

BIM and Lean are the most representative emerging approaches of the current panorama in the construction sector, but they have been developed in different fields independently. However, their joint application allows to achieve a complete implementation by preserving an entire operation throughout the project, since they act, as mutual facilitators and catalysts. This mutual synergy occurs throughout the project life cycle from the initial design to the building maintenance [42]. In all these stages the use of BIM contributes directly to the achievement of Lean objectives, and at the same time Lean processes facilitate the adoption and the continued use of the BIM model throughout all stages of the project. The synergy of both paradigms has strategic advantages in the organizations that implement it, materialized in customer focus through an early identification of value, conflict detection, fast assessment of alternatives, and collaboration, among others. Some authors have conducted theoretical studies on the integration of BIM and Lean in the design phase [43], in particular the capacity of BIM to reduce waste in the design phase. The authors identified that the most important causes of waste in the design phase are related to design changes, poor decision making, lack of information exchange, lack of communication and lack of knowledge. Given this situation, the integration of both disciplines is emerging as the appropriate solution in this design stage to reduce design times, reworks and conflicts [44], at the same time that increases predictability, and the interaction of stakeholders [45]. Within the design phase, other authors analyze how the BIM-Lean synergy allows to reduce design errors by improving communication between all agents as well as the delimitation of roles and reorganization of the work structures. This lets to identify omissions and errors before they have a late impact on the construction phase. However, all the above literature focuses only on synergies in the design phase and does not cover other phases of the project life cycle [46].

Other authors develop the synergy in other phases such as the construction stage. In this phase Lean acts as a BIM facilitator to promote collaboration through Lean tools such as large room, knotwork or Last planner, improving stakeholder's communication, setting up responsibilities and establishing adequate and concise instructions, fostering a correct implementation of BIM [47]. Also in the construction stage, it is remarkable the benefits obtained from the result of the visualization with 3D modelling. Visualization beyond the design phase, that is, during the construction process, will allow Lean principles to achieve better project performance, increasing productivity and quality and reducing the cost and delivery time of the project.

However, the literature shows the low volume of papers addressing the synergy of both paradigms when compared to the large volume of literature on Lean and BIM independently [48]. This is further accentuated if we go beyond reviews of theoretical literature. Authors have verified that there is hardly any research in indexed journals that focus on the integration of these paradigms to validate and demonstrate the viability of existing theoretical hypotheses through case studies. Some of the

few studies that address this issue only focus on the facilities chapters, as in Reference [49] where BIM and Lean synergies are validated through a case study developed in the construction phase, but which only focuses on the management of Mechanical, Electrical and Plumbing (hereinafter MEP) works, such as plumbing and electrical facilities. Similarly, in Reference [50] some authors analyse the implementation of both paradigms, but only focus on the facilities management phase. The same is presented in Reference [51] where the integration of BIM and Lean concepts such as the Last Planner System is validated in the operation and maintenance phase.

In addition, during the literature review, it was identified that none of the previous research validating the synergy, even in other phases of the project life cycle, were developed in Spain. Some of these studies carried out at an international field were the development of the Great Istanbul Airport project under a successful integral BIM Lean approach [52], which was extended to both the design and the construction of the project. Another research analyzed was the development of the metro rail station project in India, where in Reference [53], the implementation of BIM and the Last Planner System was analyzed and compared with another metro rail station project where BIM was implemented without the Lean support. The main results showed how lean practices created a culture of coordination, improved coordination within the project team and enabled BIM adoption maximizing its use for decision making. Similarly, in Reference [54] two case studies of residential construction projects were developed and analysed, determining the validation of synergy regarding better decision making and greater control both in the short and medium term through single information source, automated clash checking, visualization of process status and online communication of product and process information. Finally, in Reference [55], synergy and integration through a coordinated use of Last Planner System and BIM was analyzed, validating the interaction and communication of different project stakeholders around BIM management in planning meetings.

3. Research Approach

Although much research has been done on the application of BIM and Lean paradigms individually, there is a lack of research on the synergy of both paradigms. This is aggravated if we narrow the search to a more practical approach that moves away from theoretical research. The literature review has made us aware that there is hardly any previous practical research that combines both paradigms. Therefore, the aim of this research is to provide knowledge and evidences in an empirical way to this area so little explored, or this, the study adopted on a constructive research approach with qualitative methodology defined and validated through a case study. Case study is presented in some works as the most appropriate research method for presenting the information in the context of a particular project, inclusive of the project's characteristics and give actual project data, making possible generalisation from case-studies. It is described as a useful method to identify potential benefits of the system, especially those that are intangible, to determine its importance, as well as provide the best correlation with real-life situations. Several studies have already adopted a case study approach, such as in Reference [56], where a case study approach was adopted to explain the dynamic quality control model that was developed from a comprehensive review of the literature and site investigation. Similarly, in Reference [57], BIM benefits and the impacts on project efficiency were analysed via case studies within a large industrial setting where similar projects were evaluated, some implementing BIM and some with traditional, non-BIM approaches. Also, in Reference [58], due to the lack of case studies identified in the literature review, and to provide empirical evidence of the value and challenges of BIM, a case study of Northumbria University's city campus, was used to empirically explore the value and challenges of BIM in facility management. Also, in Reference [59] a case study of BIM deployment in a hospital construction project was developed to serve as an example of BIM implementation and collaborative work in construction projects, in order to provide findings about key factors influential to enable digital collaboration.

Furthermore, it is a fairly widespread method to provide empirical evidence on the application of the BIM or Lean paradigms independently. According to the above, the authors adopt this

approach, being aware of the limitations of the present research, regarding the need for more empirical observations, which currently make it impossible to carry out a quantitative analysis.

The research methodology included three different phases: a first phase defines the problem or deficiency upon review of the literature, a second phase presents the development of the case study carried out in the research and finally a third phase includes the analysis of data obtained and the comparison with data of other public projects. Figure 3 shows the overall research framework adopted by the authors.

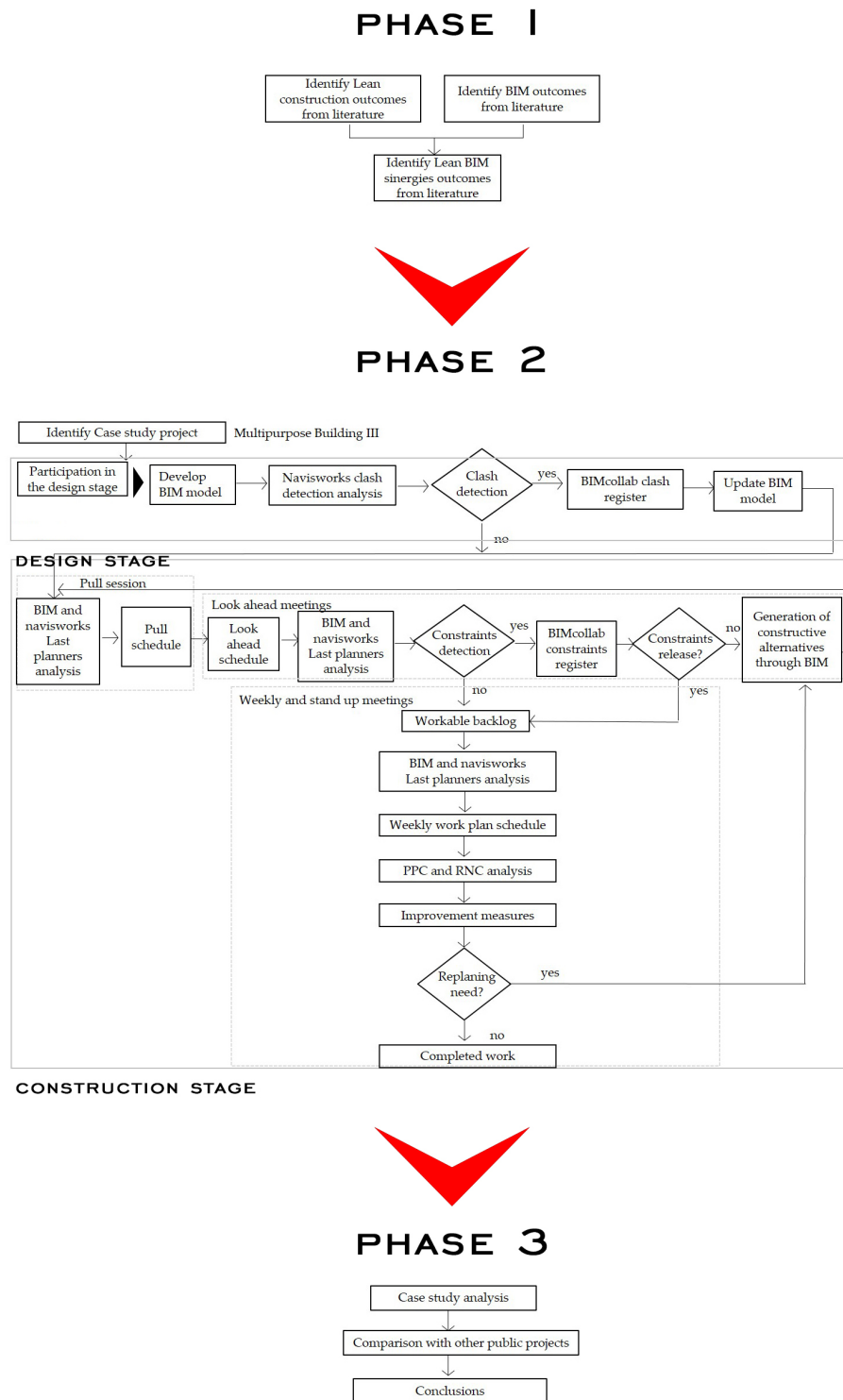


Figure 3. Overall research framework.

The first phase included the outcomes from literature not only about BIM and Lean construction but also about the BIM and Lean construction synergies. The second phase consisted of a case study where BIM and Lean paradigms were applied during the construction phase of a public building extension, the Multipurpose Building III at The University of Alicante. This research phase included the development of the BIM model during the design phase and its updating throughout the entire construction phase. Also, researchers introduced the Lean construction culture to the construction company, guiding the last planners of the construction companies and subcontracted companies in the application of the Last Planner System, recommending processes derived from literature. Researchers used the navisworks BIM management tool in the look ahead and weekly meetings, to visualize possible clash detection and to analyse potential constraints about design, pre-requisites, spaces, information, building materials or resources. Also navisworks tool allowed visualization, facilitating the quick generation of constructive alternatives in the look ahead and weekly meetings, as well as the automatic replanning. In the case of detection of constraints or clashes, these were recorded, typed, listed by priority and classified according to the phase where they were identified through the BIMcollab tool. BIMcollab is a management platform for ISSUE management, that is, problems in the cloud, and it is a tool for collaboration that allows communication on standards-based BIM models accepted from the IFC (Industry Foundation Classes) and BCF (BIM Collaboration Format). Specifically, it was used as a BIM tool to support Lean construction in relation to the constraints log, integrating updated information while providing ubiquity and transparency as it was accessible by all selected users from any device. It allowed the integration in the model of all information related to constraints log that commonly is developed manually in the Last Planner System, without computerizing. In this line BIMcollab allowed us to assign a constraint identification, to associate a resolution responsible and a deadline by way of commitment of the person responsible for the resolution of the constraint. Furthermore, it enabled us to link to her agents to the constraint to which the system automatically notified on the incidence, besides, it was possible to select user visibility, to prioritize constraints and to select areas and levels where the clashes were detected, as well as to attach images and documents associated with the incident. During the whole process, continuous improvement tools associated with lean construction such as five why's -used during the analysis of the percentage of plan completed (PPC) and the subsequent analysis of Reasons for Non-Compliance (hereinafter RNC)-, or the plus delta boards at the end of all meetings were used.

Finally, the third research phase contemplated the analysis of the process in terms of time and cost, as well as the comparison with the deviations data of other public projects which were managed with traditional methods of construction.

4. Construction Management of a Public Building

Based on the above, the present work includes a case study focused on the extension of the former building of the Faculty of Education at The University of Alicante, called Multipurpose Building III, where BIM and Lean tools were used in order to improve the construction project performance. The extension project of the Multipurpose Building III included two parts, the first one included the refurbishment of the existing building while the second part focused on the extension of the building, that is, a joining new construction building. The experimentation focused on the extension of new construction, and specifically, it focused on the analysis of benefits and improvements of using BIM tools for the detection of constraints at the Look Ahead Schedule phase of the Last planner system.

The former building of the Faculty of Education in the Campus of the University of Alicante was built in 1940, it was one of the buildings of the military airport established after the Spanish Civil War as a substitute of the first commercial airport of the province of Alicante set in 1919. In 1978, when the University of Alicante was founded, the activity of the airport finished and all the buildings became part of the Campus. Since that time this building has been home to different faculties and services and has undergone modifications and extensions.

The project objective was to value the oldest part of the building and distinguish it from the additions made in the 1980s, and to carry out an extension of the building in a new module distinguished from the old one.

The extension of the building has two levels. The project arranged classrooms in the ground level leaving the upper level for offices of different departments of the campus. The total built area was 2421 m² and the building cost was around 2 million euros.

The construction company that won the construction project in the public tender convened by the University of Alicante is a Spanish corporation of recognized prestige with an experience in the sector of 70 years and a turnover of 1,069,318,000 €, which operates both nationally and internationally and currently occupies the first position in the sectorial ranking of residential building construction at national level. Specifically, during the project execution, the main company managed the construction work that was mostly carried out by different subcontractors, 13 companies in particular. This was a consequence of both the construction crisis in Spain in recent years which has led to a reorganisation of the business structure in the companies in many companies, and the regulations of the contracting system in Spain, which allows the main contractor to subcontract practically all the work. Both the main company and the 13 sub-contractors had no previous experience in site management with a BIM model, being the first construction project they faced in a BIM environment. Similarly, they were not familiar with the Last Planner System and the associated Lean tools used in Look ahead meetings. In each of the Look ahead meetings and the meetings held within the weekly work plan framework, the site manager, the foreman, the designers, the heads of each of the subcontractors participating in the corresponding week and the four members of the research team who guided the meetings. The contractual deadline was 15 months, and the project was delivered about three weeks before, so the final delivery deadline was 14 months.

Bim and Lean Synergies in the Construction Work of the Multipurpose Building III

As it was previously highlighted the use of BIM during the design phase fosters benefits derived from visualization of 3D information models, and the coordination of the different disciplines Architecture, Structure and MEP. During the experimentation process an adaptation of the Last Planner System was carried out as a proactive management system, but extended to the design phase during the project development under the BIM framework. Initially the design team carried out the project in 2D. With the incorporation of the research team into the project, the BIM model began to be used and the adaptation of the Last Planner System was made extending it also to the design phase, as well as the use of other lean tools. In these sessions prior to the start of construction work, the projects were compared and some conflicts in the design phase were detected. As a result of this adaptation, the conflict analysis, the registration of these conflicts and the updating of the model was carried out. These conflicts between disciplines were identified in the early design phase, avoiding later reworks, delays and overruns during the execution of the construction project.

Furthermore, during the construction stage the Last Planner System was applied together with other Lean tools that facilitated its implementation. The use of the BIM model during the look ahead meetings carried out on site facilitated the early identification of constraints through the visualization and analysis of the model in the 40 Look ahead meetings (LAM) and the Weekly Work Plan meetings both held weekly during the construction phase.

A detection of conflicts was made through the visualization of the BIM model. However, the proactive management that allowed better decision making and a higher quality of what was executed, avoiding bad practices and reworks, took place through the early management carried out during the look ahead sessions, within the lean construction framework. During the identification of these conflicts or restrictions, the root cause of the problems was identified with lean tools, and commitment dates were set for the removal of these restrictions in addition to the responsible persons who were assigned to each restriction. This management was again fed back to the tools associated with the BIM model, in this case the BIMcollab tool, which made it possible to computerize,

record and integrate information on the restriction, the person assigned and the maximum date on which it had to be resolved before it affected planning. This proactive management made it possible to avoid deviations from deadlines and costs, which are quantified below.

A summary table (Table 1) of all the conflicts and deficiencies detected throughout the case study is shown below. The table also includes the date of constraints detection, the construction date, and consequently, the anticipation in weeks that avoided an incidence in the construction work or facilitated better decision making. Also, the economic quantification of extra cost and delays, as well as other aspects related to the quality that generated the synergy of both paradigms. The sum of the impact of all deficiencies would have been a 4-week delay, considering overlaps in time, and the extra cost avoided amount to 86,191.70 €. In addition, the use of BIM and Lean not only prevented delays but also allowed the work to be completed 3 weeks before the contractual term of the project, as shown throughout the present work. The economic estimations were made according to the unit prices of the project and the contract, while term estimations were determined according to the work planning and the participants' expertise.

These constraints detected both in the design and construction phase of the project will be developed throughout this section.

Table 1. Summary of incidents and deficiencies identified throughout the case study.

| Id | Constraints | Detection Date | Construction Date | Time Ahead | Quantified Delays Avoided | Quantified Economic Savings | Quality Issues |
|-------|--|----------------------------------|-------------------|----------------------------------|---------------------------|-----------------------------|---|
| ID_01 | Interference of the slab of one of the stairs with a window in the modern building | Design stage | Week 16 | 68 weeks ahead | 4 weeks | 4,760.00 | Demolition of stairs and rework |
| ID_02 | Intersection of the sunshades with rainwater downpipes | Design stage | Week 29 | 81 weeks ahead | 2 weeks | 7,425.60 | Remove and modify parasols and rework |
| ID_03 | Conflict of heights of the false ceiling by the edge beams, the air conditioning ducts and the height of the windows | Design stage + LAM 09 in Week 05 | Week 09 | 61 weeks ahead and 4 weeks ahead | 1 week | 13,923.00 | Remove ducts, modify windows and rework |
| ID_04 | Conflict with the layout of the air conditioning ducts in the computer room with the luminaires and other ducts | Design stage + LAM 09 in Week 05 | Week 09 | 61 weeks ahead and 4 weeks ahead | 1 week | 2,915.50 | Modify ducts and rework |
| ID_05 | Crossings in the corridors between the different facilities located in the false ceilings | Design stage + LAM 09 in Week 05 | Week 09 | 61 weeks ahead and 4 weeks ahead | 1 week | 4,331.60 | Relocate facilities |
| ID_06 | Optimization of the modulation of the large format porcelain (Large Format Ceramic) as interior facing in the baseboards of the corridors of the entire building | Initial meeting. | Week 10 | 20 weeks ahead | No quantification in time | No economic quantification | Worst aesthetic. |

Table 1. Cont.

| Id | Constraints | Detection Date | Construction Date | Time Ahead | Quantified Delays Avoided | Quantified Economic Savings | Quality Issues |
|-------|--|-------------------|-------------------|----------------|---------------------------|-----------------------------|---|
| ID_07 | Space for air conditioning machines on one of the toilets of the old building and its form of access | LAM 10 in Week 06 | Week 10 | 4 weeks ahead | 2 weeks | 13,090.00 | Ceiling modification and disassembly machines. Reworks |
| ID_08 | False ceilings and suspended elements bolt in concrete beams instead of in the ceramic vaults in the modern building | LAM 13 in Week 09 | Week 13 | 65 weeks ahead | 2 weeks | 5,355.00 | Future Maintenance Issues |
| ID_09 | Location of the machines on the roof and design of the layout of the ducts and pipes for servicing it | LAM 26 in Week 22 | Week 26 | 4 weeks ahead | 3 weeks | 11,186.00 | Mount and disassemble ducts. Reworks. Difficulties for future maintenance |
| ID_10 | Slope options in the underneath slab of the yard and the level of access in the classrooms of the north façade | LAM 31 in Week 27 | Week 31 | 4 weeks ahead | 2 weeks | 23,205.00 | Water entry into the classrooms. Future modification of slope formation throughout the yard |

Figure 4 shows the phase schedule of the construction project, some of the conflicts detected at the design phase and during the last planner session meetings required an update of the model and a replanning. This replanning, in a generalized way, is never carried out in the construction work managed in a traditional way, however thanks to the use of BIM environments the replanning was immediate, and all the stakeholders had access to real and truthful information in real time. The automatic generation of changes in the schedule is one of the most relevant synergies of applying both paradigms since in a traditional way the updates do not occur in many cases (update of both the planning and the BIM model) and with the joint application of both paradigms a continuous update is ensured to keep both the model and the replanning alive.

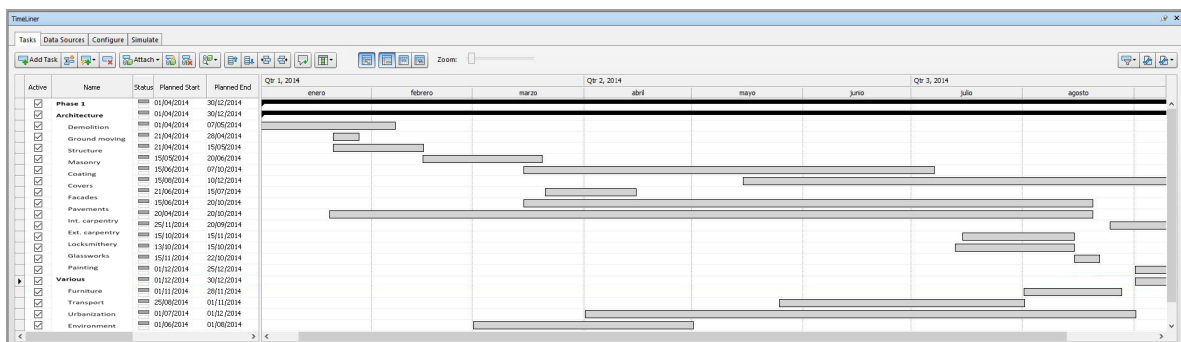


Figure 4. Possibility of immediate replanning in the Business Information Modelling (BIM) environment and access to real and truthful information in real time by all agents.

The use of BIM models made possible conflict detection, whereas this would not have been possible through the use of traditional 2D models. The next figures represent some examples of conflicts detected from the 3D models in the design phase showing their invisibility in the 2D planes.

Figure 5 shows the interference of the slab of one of the stairs with a window of the modern building (ID_01). As shown in Figure 2 this detection was carried out before the beginning of works, still in the design phase. If the project had not been developed under BIM methodologies, it would have caused a conflict on site during the masonry construction work at week 16. This early detection, 68 weeks ahead its construction date, allowed an optimum stakeout of holes in the façades before even

managing the carpentry purchases and without modifying the balance of the projected architecture nor the calculations of energy efficiency by quick decisions on the site. This detection of conflict prevented a later demolition of the staircase and its subsequent re-execution. Therefore, the quantification of the avoided deviations was estimated in 4 weeks of avoided delays and an economic quantification that would amount to 4760 €.

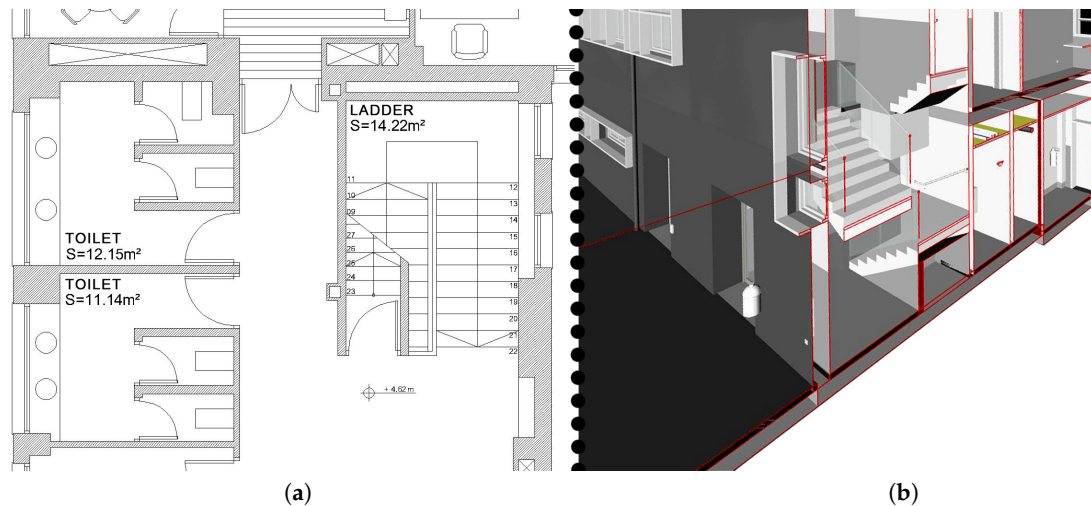


Figure 5. Window-stairs conflict (a) 2D display difficulty and (b) easy detection in the BIM model.

Likewise, some conflicts were avoided at the design stage due to the coordination of the different disciplines such as Architecture and MEP. Specifically, Figure 6 shows sunshades intersection of modern building with rainwater downpipes (ID_02). This type of intersection conflicts can only be identified when real-sized data crossing occurs in BIM environments. On the contrary, in the 2D models pre-dimensioned it is hard to detect the early identification of these problems. Again, this conflict was identified before the beginning of works at the design phase, 81 weeks ahead the construction date, this implies a long time to find appropriate solutions without site improvisations. If the project had not been developed under BIM methodologies, it would have caused a conflict on site during the metal structural work at week 29. It would have paralyzed the project, and would have led to modifications in the original project, with the subsequent reworks. In addition, the project would have been delayed due to slowness of changes, since it would not have been a parametric drawing, the automation in the modification of drawings and views would not have been possible, and therefore, the costs of the project would have been increased and there could have been errors and inconsistencies between the project drawings. The quantification of economic deviations was estimated in 7,425.60 euros and two weeks of delay.

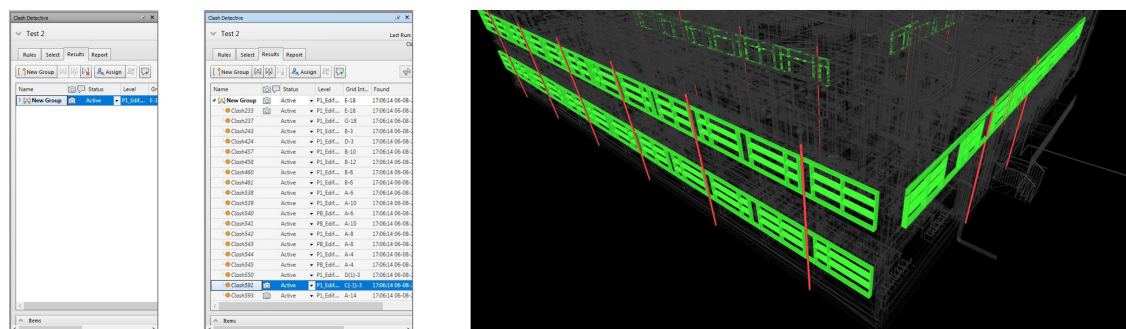


Figure 6. Sunshades intersection of modern building with rainwater downpipes.

Other conflicts identified on the design phase through the use of BIM and the coordination of disciplines related to the duplicate information and the information gaps of the project were the anchoring of false ceilings and suspended elements in concrete joists instead of placing them in the ceramic vaults (ID_08). This would have caused future problems and maintenance costs during the use phase of the building, in addition to delays in the construction work of 2 weeks to re-perform its correct execution and an economic estimate of 5355€.

Similarly, the height conflicts in the modern building due to intersections of the false ceiling with the edge beams and the air conditioning ducts and the height of the windows (ID_03), or conflicts with the layout of the air conditioning ducts in the computer room with the lights (ID_04), among others. The identification of these intersections avoided later deficiencies and problems on site, as well as facilitating decision-making under non-stressful conditions. This modification of ducts and their re-execution, was quantified in savings of one week and 13,923€ for ID_03 and savings of one week and 2915.50€ for ID_04.

Next, an image of the conflict ID_03 identified in the previous is shown (Figure 7), which reveals how the collision between the false ceiling, the structure and the installations was initially and how it was later, after the coordination of the last planners and agents involved in these tasks, and how through the visualization of the model an efficient solution could be reached in the LAM 09 meeting.

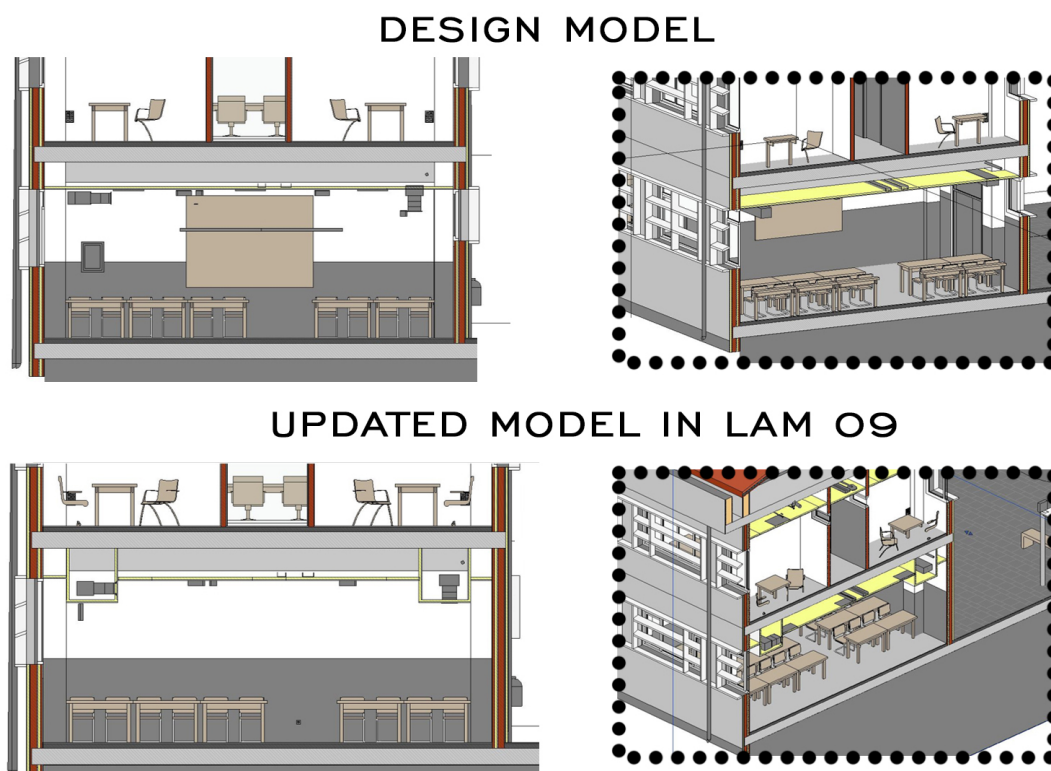


Figure 7. ID_03: Evolution of the design model to a consensual solution by the intervening agents.

Lean enhanced the use of BIM and extended it not only to the design phase but also to the entire project life cycle. In this sense, the use of Last Planner System as a Lean Construction tool improved the performance and management of construction activities by reducing uncertainty during its planning and execution. During the Look a head meetings it was possible to identify more conflicts that arose during the execution of the work by changes of decision during the same, or simply for the constructive improvements proposed by the stakeholders and those responsible for each task in the meetings.

In this sense, it is remarkable the visualization of the BIM model and the multiusers viewing of merged and separated multidiscipline models during the Look Ahead meeting of week 9 held in week

5 with real dimensions of crossings between different installations in false ceilings of corridors (ID_05). This made it possible for designers, engineers, operators and all stakeholders to fully collaborate and be involved in the process through their knowledge and the establishment of their real needs, avoiding quantified deviations of 1 week and 4331.60€ for the relocation of facilities. In short, it was possible to integrate and create a team by improving knowledge and its transfer, thus encouraging continuous improvement. The same happened in the LAM 26 held in week 22 (ID_09), where the optimal solution for the location of machines on the roof and the layout of the ducts and pipes for servicing it, was a solution agreed by all trades involved (Figure 8). Furthermore, through BIM it was possible to recreate the possible workspaces on roof during the work as well as its collision in navisworks, creating masses that simulated the workspace or passing places, and verifying that this space was effectively maintained during the construction works. If this proactive management had not been carried out, future pathologies would have manifested in addition to extra costs during the execution of work when assembling and disassembling ducts and pipes. These work of disassembly and rework were quantified in 3 weeks and 11,186€.

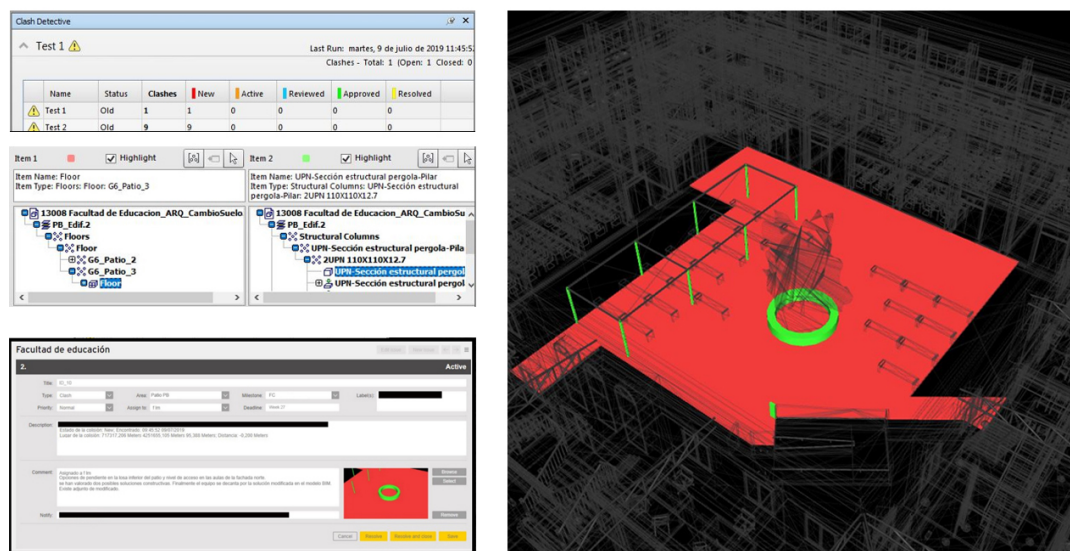


Figure 8. Management of conflict in work detected in Look Ahead Meeting (LAM) 31 through navisworks and registration of the conflict through BIMcollab.

Furthermore, other conflicts were avoided at the construction stage using the BIM model as a prototype. The visualization of the slope options in the underneath slab of the yard and the level of access in the classrooms of the north façade (ID_10) is a good case in point, where it was assessed which elements were geometrically affected. As shown in Figure 9, through the use of the navisworks management tool it is shown that elements entered into conflict when modifying the ground, the elements external to the conflict were turned off and the elements that intersected were highlighted in red and green. In this way, during the meeting it was possible to assess the possible consequences, allowing all the agents involved to contribute their vision. The BIM prototype allowed the whole team to visualize different solutions during the Look Ahead meeting held in week 27 for activities performed in the week 31. Therefore, through the LAM 31 and the BIM visualization the stakeholders anticipated one month the identification of the matter. Rapid generation and evaluation of construction alternatives was possible through the visualization of the form. This fact not only allowed them to make better decisions without improvisation but also to count on the commitment and collaboration of those who carried out the activity. With this anticipation, future flooding in the classroom were avoided, and a correct execution was carried out. Savings of this constraint were

quantified in 2 weeks and 23,205€. The visualization and simulation during the construction process allowed stakeholders, including workers in charge of slope formations, to achieve better project performance, increasing productivity and quality through the Last Planner sessions.

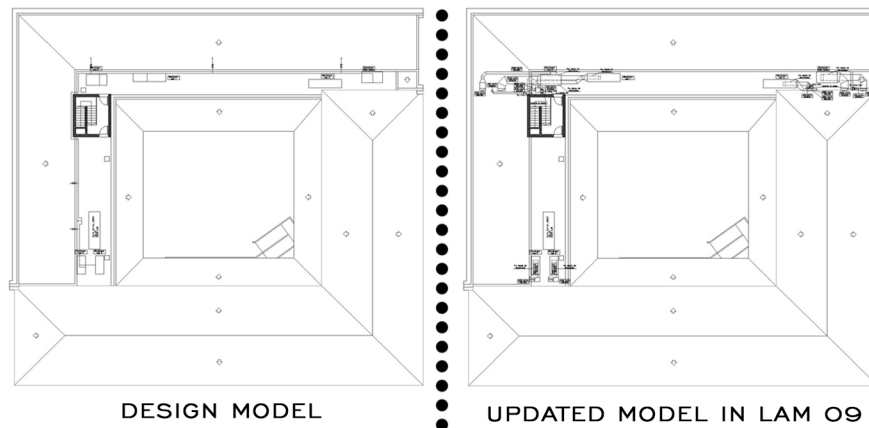


Figure 9. Through BIM it was possible to recreate the possible workspaces on roof 2D drawings with impossibility to visualize workspace masses.

Also, BIMcollab allowed us to register the constraint, and to associate a resolution responsible as it is shown in the box highlighted on the left side of the image.

Moreover, it enabled us to link other agents to the constraint to which the system automatically notified on the incidence. For data protection some items have been crossed out. The conflicts shown in BIMcollab were linked to positions in the model, which were followed from the web browsers during the process. BIMcollab also provided the option of receiving a weekly summary of conflict activities, this information being used in weekly meetings to implement continuous improvement lean tools such as the 5 Why's, which is a method based on asking questions to explore the cause-and-effect relationships that generate a particular problem.

5. Comparative Analysis, Research Findings and Discussion

Throughout the present research, it has been determined that although the implementation of the BIM represents great benefits in the building process, BIM tools by themselves cannot guarantee efficient construction processes, so the use of Lean Construction tools are essential to fulfill BIM tools function in its totality. The use of BIM tools allows the identification of all the restrictions in a proactive way through the Last Planner System meetings and the consensus of the optimum solution on the part of the stakeholders. Specifically, the use of BIMcollab tools made it possible to manage conflicts in a structured manner throughout the last planner implementation process, as well as to integrate and share the problems identified.

In addition, the results of the case study allow us to make a comparison with the data related to time and cost deviations of other public projects (Table 2) which were managed with traditional methods of construction. In this line, Spain does not have centralized records in which these data can be assessed in an integrated manner, and is not easily accessible. However, it has been possible to contact three administrations, national, regional and local, which have provided comparison examples with different uses, sizes and project complexity. For a long time, for a Spanish administration it is considered that a project and its construction have been drafted and managed properly if the budget deviation is at the end of construction below 10%.

Table 2. Comparative data analysis of nine projects of different public administrations and the case study. Data derived from the case study.

| Code | Budget (€) | Built Area (m ²) | Ratio (€/m ²) | Type of Building | Type of Intervention | Budget Deviation (€) | Deviation Percentage | HVAC Deviation (€) | HVAC Percentage | HVAC Complexity |
|------|--------------|------------------------------|---------------------------|------------------|----------------------|----------------------|----------------------|--------------------|-----------------|-----------------|
| B 01 | 4,011,967.81 | 4789.00 | 837.75 | E | E | 798,774.68 | 0.199 | 649,410.31 | 0.81 | High |
| B 02 | 812,260.89 | 818.61 | 992.24 | R | RV | 48,426.50 | 0.060 | 22,536.00 | 0.47 | Low |
| B 03 | 709,634.97 | 450.14 | 1576.48 | E | NB | 49,674.45 | 0.070 | 7202.79 | 0.145 | High |
| B 04 | 1,535,474.41 | 1150.50 | 1334.61 | DCC | NB | 146,301.19 | 0.095 | 24,871.20 | 0.17 | High |
| B 05 | 2,024,745.66 | 1333.86 | 1517.96 | DCC | NB | 184,251.86 | 0.091 | 24,874.00 | 0.14 | High |
| B 06 | 2,054,406.45 | 3060.37 | 671.29 | M | NB | 165,688.93 | 0.081 | 10,352.64 | 0.06 | Low |
| B 07 | 1,106,439.84 | 773.63 | 1430.19 | R | NB | 95,401.00 | 0.086 | 21,744.00 | 0.23 | Low |
| B 08 | 1,655,635.83 | 1376.99 | 1202.36 | DCC | NB | 162,252.31 | 0.098 | 19,656.23 | 0.12 | High |
| B 09 | 932,029.58 | 1238.67 | 752.44 | DCC | RV | 83,267.25 | 0.089 | 12,490.09 | 0.15 | High |
| CS | 1,912,332.00 | 2438.80 | 784.13 | E | E | 24,942.17 | 0.013 | 13,671.09 | 0.50 | High |

Public administrations provided 9 cases that together with the present research, carried out by the research team, form a sample of 10 elements. The condition was to obtain complete information about the project and work management, confirming that none of the nine was managed using neither BIM nor Lean paradigms. In addition, after knowing the results of the project developed under the BIM and Lean framework, another condition was that it should be possible to catalogue the management of the work and the economic result of both the architectural construction and the facilities separately.

All the buildings included in the comparison, and described below, are of public initiative and most were built by SMEs. Building B01 was a public project that consisted of an extension of an old market with change of use to educational building, it was a large building of 4789 m² built by a Spanish large company with a construction deadline of 24 months. Building B02 was a public project for social residential use that consisted of a renovation without change of use, it was a small project of 818.61 m² built by an SME with a with a construction deadline of 15 months. Building B03 was a public project where a new building was built for educational use, it was a small project of 450 m² with a construction deadline of 15 months. Building B04 was a public project that consisted of a new building for day care centre use, it was built by an SME with a with a construction deadline of 17 months and a built area of 1150.50 m². Similarly, Building B05 was a public project that consisted of a new building for a day care centre use built by an SME with a with a construction deadline of 17 months and a built area of 1338.86 m². Building B06 was a public project for a new building construction with a multifunctional use to host associations for the care of people with generalized disorders, it was built by an SME with a with a construction deadline of 20 months and a built area of 3060.37 m². Building B07 was a public project with a built area of 773.63 m², a deadline of 15 months built by an SME and a residential use as a reception centre for minors. Building B08 was a public project with a built area of 1376.99 m², it was a new building with again a day care centre use, executed by a SME in a period of 18 months. Finally, building B09 was a renovation of a building that kept its use of specialized centre of attention for elderly people, the building was also a public project built in 18 months with a built area of 1238.67 m². Finally, the case study named as CS in the table is an extension project with educational use and a built area of 2438.80 m².

As can be seen in Table 2, the building samples (B) were classified according to their size and complexity of the conditioning system. They were classified as small buildings those with a smaller floor area of 1000 m², medium buildings those with a floor area located between 1000 m² and 3000 m² and finally, were considered as large buildings those that exceed 3000 m². In addition, a classification was made based on the use since it has an impact on the construction ratio per m². Examples of both new buildings (NB), extensions (E) and renovations (RV) were included, as well as distinguishing between Day Care Centre (DCC), Multifunctional (M), educational (E) and residential (R) buildings.

The analysis of budget deviations allowed us to affirm that there is no clear relationship between the complexity of the building, its use and the budget deviation. However, it was possible to detect greater conflicts during the construction of buildings with complex conditioning systems.

As can be seen in Table 2, the total average deviation of the nine examples analyzed was around 9.7%, being approximately 75% of this deviation due to architectural construction issues and 25% due to the facilities. However, the data obtained in the case study (Table 3) showed improvements in this regard, the case study where was implemented a combined application of BIM and Lean procedures in construction work showed a considerable reduction in budget deviation. This extra cost has been minimized with

respect to the rest of the projects included in Table 2, resulting in a budget deviation of 1.3%, of which 11% of the total percentage of cost overruns correspond to brickworks unit, 8% from the roof unit of the architecture chapter. However, data analysis shows that the highest percentage of deviation lies on the facilities chapter. Specifically, the highest percentage refers to HVAC with a 71% of cost overruns.

Table 3. Data derived from the case study.

| Chapter | Company | Budget (€) | Deviation (€) | Deviation (%) |
|-----------------------|--|---------------------|------------------|---------------|
| Demolition | Subcontractor 1 | 59,804.53 | | |
| Excavation | Subcontractor 2 | 2431.81 | | |
| Foundation | Subcontractor 3 | 4205.83 | | |
| Structure | Subcontractor 3 | 35,740.46 | | |
| Brickwork | Subcontractor 1 | 90,377.95 | 2079.14 | 11% |
| Coating | Subcontractor 4 and Subcontractor 5 | 95,343.37 | | |
| Roof | Subcontractor 6 | 17,356.01 | 1483.29 | 8% |
| Façade | Subcontractor 7 | 119,098.81 | | |
| Floor | Subcontractor 5 | 168,592.54 | | |
| Wood Carpentry | Subcontractor 8 | 52,150.80 | | |
| Metal carpentry | Subcontractor 9 | 147,177.68 | | |
| Locksmithing | Subcontractor 9 | 29,575.63 | | |
| Stained glass windows | Subcontractor 9 | 30,795.13 | | |
| Painting | Subcontractor 10 | 33,713.71 | | |
| Several | Main construction company | 11,708.16 | | |
| Furniture | Subcontractor 11 | 22,280.61 | | |
| Urbanization | Subcontractor 1 | 88,726.48 | | |
| Total Architecture | | 1,009,079.50 | | |
| Previous | | 23,695.27 | | |
| CT | Subcontractor 12 | 83,976.33 | | |
| Electricity | Subcontractor 12 | 271,807.68 | 6440.92 | 34% |
| Plumbing | Subcontractor 13 | 19,211.36 | | |
| Sanitary drainage | Subcontractor 13 | 19,408.97 | 138.48 | 1% |
| Fire | Subcontractor 13 | 28,470.60 | | |
| Voice and data | Subcontractor 12 | 51,156.81 | 1129.26 | 6% |
| PA system | Subcontractor 12 | 10,388.71 | | |
| HVAC | Subcontractor 13 | 337,340.20 | 13,671.09 | 71% |
| Total Facilities | | 845,455.93 | | |
| Control | | 20,303.43 | | |
| Quality | | 6392.34 | | |
| Residues | | 6066.92 | | |
| Health and safety | | 25,033.87 | | |
| TOTAL | | 1,912,332.00 | 24,942.18 | |

The analysis of the results shows that the management and control of facilities is the part of the construction project that requests more attention. The synergy of the use of BIM and Lean paradigms during the development of the case study of a public construction project at the university of Alicante minimized the conflicts in the architectural chapter, and although it also reduced the conflicts of the part of facility systems, conflicts and budget deviations continued to exist with a considerable percentage.

6. Conclusions

BIM and Lean have been implemented independently on many projects, and many researches have been conducted to study more deeply in a theoretical framework the benefits of applying these paradigms not only isolated but also jointly. However, few researches show a case study of both paradigms applied to a public construction project. The case study presented in this paper shows the benefits of applying the BIM and Lean paradigms in order to improve the construction project performance of a public building extension, the Multipurpose Building III at The University of Alicante.

Firstly, the implementation of both paradigms during the case study and the monitoring of the project has allowed us to verify in a practical way all the benefits read repeatedly described in the literature especially the most intangible such as improved communication, information flow, easier determination of improvements in constructive solutions, and better decision making without improvisation. All this has brought benefits to the project in terms of productivity improvements, workflow improvements, improvement in health and safety, improvement in environmental quality.

Secondly, the experimentation found more tangible improvements in terms of reduction in material usage, since it has been possible to make better layouts and cuttings of constructive elements such as Large Format Ceramic and other ceramic elements through the BIM environment and the anticipated management within the Last Planner System. Also, several improvements have been identified in the outcomes related to time and cost, through the detection of constraints at the design phase and Look ahead meetings of the Last Planner System during construction phase. The sum of the impact of all deficiencies would have been a 4-week delay, considering overlaps in time, and the extra cost avoided amount to 86,191.70 €. In addition, the use of BIM and Lean not only prevented delays but also allowed the work to be completed 3 weeks before the deadline which was stipulated in 15 weeks contractually. In addition, the research has allowed us to establish at a practical level that BIM and Lean effectively empower each other. We verified that BIM directly supported the lean objectives, facilitating the visualization, communication, transparency, immediate replanning and proactive management and control, among others, but at the same time the Lean processes facilitated the adoption and use of BIM, preventing the BIM paradigm from being distorted and favouring the continuity and implementation of the BIM model beyond the design phase.

Finally, the comparative analysis of cost deviation in other public projects managed in a traditional way carried out in the present work, showed that there is no clear relationship between the complexity of the building, its use and the budget deviation. However, it is possible to detect greater conflicts during the construction of buildings with complex conditioning systems. Furthermore, the total average deviation decreased 8.2% due to the application of BIM and Lean paradigms, where deviations due to architectural construction issues have been minimized considerably and having practically all the deviations its origin in the installations chapter.

Future research will focus on the development of more case studies to obtain more comparative results, in addition to the search for causes and identification of tools under the BIM and Lean paradigm that can reduce these deviations from the scope of the facilities.

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