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Implementation of an interoperable process to optimise design and construction phases of a residential building: A BIM Pilot Project

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ABSTRACT

Building Information Modelling (BIM) represents a long-term investment that could allow time reduction and a cost enhancement by means of optimised design and construction processes. The paper focuses on the first official Italian Public Pilot Project, dealing with the implementation of BIM-based validation and construction optimisation in a construction process. The case study concerns a residential building located in a dense urban district, causing a confined construction site affected by space shortage and coordination issues. The research aims to implement an interoperable IFC-based process in order to support the design and construction phases, performing advanced Model and Code Checking and analysing the construction phase through 4D BIM. Architectural, structural, and MEP models have been enriched with alphanumeric attributes as required by semi-automatic validation processes. An auto-matching between BIM objects and construction activities was also achieved. The early results showed the possibility of a BIM-based semi-automatic validation of design choices and an improved coordination between design disciplines. Moreover, the construction site simulation allowed the comparison of different layout options and baseline schedules. The research also tested the joint use of Model Checking and 4D BIM tools in order to analyse construction progresses by exporting an IFC-based construction site configuration directly from the 4D BIM tool. The tested process created an open, interoperable, and multi-disciplinary approach. The main findings concerning the domestic special constraints are described and analysed.

1. Introduction

Building Information Modelling (BIM) has been conceived and perceived as a transformational game changer by various governmental strategies in Europe and elsewhere [1–3]. A profound shift is needed during this transformational process, indeed: Public Clients have been often involved in BIM-based Pilot Projects over Northern and Central Europe, depending on the nature of their government mandates. Several EU-28 Member States have already implemented BIM in their construction strategies in order to transpose the European Union Directive 2014/24/EU on Public Procurement stating that "for public works contracts and design contests, Member States may require the use of specific electronic tools, such as of building information electronic modelling tools or similar" [4]. UK, Germany, France, and Spain have already started to include, with different levels of maturity, Building Information Modelling methods and tools in their governmental strategies [5–12]. On the other hand, the implementation of information-based methodologies and technologies in the Italian AEC industry is just at the beginning and it lacks an effective BIM-oriented strategy.

The proposed paper focuses on the first official Italian BIM Pilot Project managed on behalf of a Central Public Body. The aim was not to implement BIM during the bid process and in the Public Procurement framework [12], but to support the Public Client in order to test advantages of BIM compared to traditional design and construction management practises and to improve coordination and collaboration between different disciplines and phases of the construction process. The Pilot Project aimed to introduce the Public Client to a different approach rather than the traditional one it currently uses, from both a methodological and technological point of view. It can be said that the focus was based on the education to BIM of the Public Client in order to transform it in an effective co-author of the project and originator of the process [13].

A BIM approach can be implemented in any tendering route, improving the overall process [1,12]. During either the design phase or the construction one, in fact, there are clear benefits in using the BIM methodology [12,14]. In the proposed Pilot Project, the chosen Public Procurement method was the Design-Bid-Build (DBB) one: the Public Client developed the preliminary and detail design, while the awarded contractor was responsible for the construction phase and had to evaluate construction costs as well as to develop the construction

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documents, including the schedule. This kind of procurement, on one hand, helps the Public Client to have a better idea of the costs, but, on the other hand, this also leads to a certain level of separation between the design phase and the construction one [1,12]; as a result, the process is characterised by a lack of knowledge and collaboration.

In a DBB procurement method, it would be possible to create a Building Information Model during the tendering phase in order to allow the bidders to fully understand the complexity of the project and to extract quantities in a semi-automatic way [12,14], leading to a better control of quantities and a more accurate cost estimation. The bidders may also link the parametric model to the construction schedule in order to better optimise the construction phase. Moreover, a more coherent and coordinated documentation could be extracted from a federated model rather than starting from traditional 2D drawings, avoiding mismatching information and controversies [12,14].

Anyway, the use of BIM in traditional procurement routes loses an important part of its positive disruptive benefits [12,15] and they may also represent a limit to an effective implementation of the digitalised process [16]. In the last few years, innovative procurement methods based on the collaboration and co-operation of the involved parties have been developed [12,17]; one of them is the Integrated Project Delivery (IPD): in this case, the use of BIM can effectively support the required level of collaboration [12,18–20].

In this Pilot Project, BIM was implemented in order to improve coordination and collaboration between different design disciplines and to validate the design phase. Model Checking was used to control the quality of the model in a semi-automatic way [21,24] and check compliance against codes and regulations at national and local level [21–23]. Moreover, this methodology was also implemented in the construction phase to create a 4D Building Information Model, which consisted in a simulation of the construction process over time. A 4D BIM is created by linking construction activities defined in a schedule to 3D objects in a Building Information Model. Developed at different stages of a construction project, a 4D BIM allows the analysis of a proposed design and its constructability, as well as the validation of construction planning and monitoring the construction progress [25–27].

2. Methodology

The proposed case study was the first official Italian Public Pilot Project for the implementation of the BIM-based validation and construction optimisation into a construction process. The Pilot Project followed a comparative approach and it was developed according to the sequences and frames devised by the Ministry of Justice in the United Kingdom [13,28] and Statsbygg in Norway [1,29].

2.1. The BIM Pilot Project framework

The experimentation took six months between 2013 and 2014; the Public Client decided to not integrate BIM directly in the Public Procurement process, but between the detail design phase and the construction one. The validation phase had already started according to the traditional, manual methodology when the BIM experimentation was introduced. This choice inevitably led to some limits in exploiting the potential benefits of the BIM implementation [30]. Anyway, the entire design and construction management processes were simulated, with a focus on the role of BIM in design validation and construction optimisation.

The aim of the Pilot Project, in fact, was to test advantages of BIM compared to traditional practises of a building process as a long-term investment for the Public Client to better control the entire process, but also to effectively improve coordination and collaboration between different disciplines and phases of an integrated process. The actors involved in the case study were the Public Client, both owner and design reviewer, an ICT partner, and the BIM research group of the Department of Civil, Environmental, Architectural Engineering and Mathematics (DICATAM) of the University of Brescia, which supported the implementation of the BIM process.

The case study was related to the BIM-based validation and construction optimisation of a new three-floor residential building with a two-floor underground car park. The architectural, structural, and MEP designs were modelled in dedicated BIM authoring software and then merged into a federated model through the Industry Foundation Classes (IFC) interoperable and neutral data format [31]. The aim was to simulate the co-operative approach implemented elsewhere in order to validate its own reliability within a confrontational environment. An IFC-based interoperable process was implemented to perform Model Checking, including compliance checking to codes, regulations, and client's requirements, and to effectively manage the construction phase linking the construction schedule to the Building Information Model into a 4D BIM. The BIM environment included two BIM platforms and two BIM tools [19]. Nemetschek Allplan 2014 was used for structural and architectural models, while DDS-CAD of the Norwegian Data Design System, currently a Nemetschek company, was the BIM authoring tool used for modelling MEP systems. Model and Code Checking was implemented through Solibri Model Checker (SMC) in order to check quality, internal consistency, and regulatory compliance of the Building Information Models. Synchro PRO was the software chosen for 4D Building Information Modelling (4D BIM) and construction management.

Moreover, geometrical and alphanumerical attributes were defined and added in the Building Information Models to be used for further BIM-based analyses.

2.2. Building model preparation according to defined BIM uses

Model Checking and 4D Building Information Modelling are the BIM-based analyses conducted during the experimentation. The purpose was the implementation of an interoperable and semi-automatic IFC-based process aimed to perform advanced Model and Code Checking and to effectively manage the construction phase through 4D BIM. To this purpose, the Building Information Model was enriched directly in the BIM authoring tool of all the informative content needed to proceed to the next phase of the analysis. An outline BIM Execution Plan (BEP) defined BIM-goals as a function of which geometrical and, above all, alphanumerical attributes were embedded in architectural, structural, and MEP models in order to answer the information requirements [32] of the Public Client that, for the first time, implemented a BIM-based process in its own procedures.

In order to provide the information model with the needed informative content [33] and to achieve a certain level of automation, a careful and detailed modelling and information management phase was performed. A deep analysis of the alphanumeric attributes to be added in BIM objects and of the suitable granularity of the parametric model was needed. In fact, building model data had to be effectively structured in order to successfully validate the informative content, geometrical and non-geometrical one, against various rule-based domains and to automatically link parametric objects, filtered by construction activity, to the construction schedule in a 4D BIM tool [25]. For both these analyses and BIM uses [34] the necessary attributes to be included in the informative content of the Building Information Model were defined [24].

Allplan native data were exported to Microsoft Excel, where the required attributes were added directly in the spreadsheet. The bi-directional link between the authoring tool and the spreadsheet allowed the informative content to be automatically modified and integrated with the necessary requirements. Moreover, the external link to the Allplan database allowed the easy management of the necessary BIM requirements for checking the model against BIM Validation and Code Checking rules. According to the Level of Development (LOD) [35] of a Building Information Model, in fact, different analyses can be conducted. For example, for Building Information Models at the design phase, a LOD 300 or LOD 350 is generally sufficient for code compliance submission [24]. Several researches at an international level have been focused, on one hand, on translating the requirements of building codes and regulations into computable rules applicable to rule-based Model Checking and, on the other hand, on the development of a parametric model featuring the required alphanumeric attributes to evaluate compliance with the rules [12,22,23,36,37]. The needed informative content depends on the validation domains according to the specific types of analysis [38]. For instance, IFC requirements for building design validation are different from the clash detection ones [21,38]. Moreover, they are also stricter than earlier drafting requirements and designers defining Building Information Models that will be used for rule-based checking may have to manually create them so that the models provide the information required according to a well-defined agreed-upon BIM Execution Plan [21,33]. In fact, differently from geometry-based BIM tools, such as the clash detection ones, a basic requirement for rule-based checking system is that each building object is well-defined by attributes such as object name, type, relationships, and metadata [38].

The same process was implemented for the 4D BIM: in order to ensure the automatism of the connection between the 3D model and the construction schedule, an appropriate parameter, named Activity ID, was associated to each element and filled according to the Work Breakdown Structure (WBS) that had been defined by the main contractor. Schedule data, such as the WBS code or the Activity ID—according to the agreed granularity of the schedule and of the Building Information Model [39]—needs to be filled in an appropriate attribute of BIM objects in order to proceed auto-matching it to the relative construction activities [38].

3. Model Checking: BIM Validation, Clash Detection, and Code Checking

Model Checking is a rule-based framework to validate design according to various validation domains [38]. It consists in a control system through which the user is able to perform a check, whose results may be "pass," "fail," "warning," and "unknown," in case of incomplete or missing data [16,40,41].

3.1. BIM-enabled design validation

Model Checking ensures quality and internal consistency of a Building Information Model [42]. Moreover, in an open BIM process, based on the use of an interoperable and neutral data format, the validation phase plays a key role in the formalisation of information exchange procedures [16]. To this end, a systematic control of parametric models should be implemented in own procedures by both clients and designers in order to improve the quality of the design solutions, their consistency with the information requirements, and their effective constructability, reducing the number of changes during the construction phase and increasing the transparency of the entire process. In fact, in standard design and validation processes, just the 5–10% of the informative content of a project is systematically checked against the 40–60% of the validated design by means of semi-automatic BIM-based Model Checking tools [42]. Furthermore, the manual validation of design solutions against building regulations is a subjective, error-prone, and time-consuming activity that may lead to ambiguity, inconsistency in assessments, and delays over the entire construction process [22].

A rule-based checking system can be implemented in two different ways. One way is the use of applications and plug-ins in BIM authoring platforms: this way architects and engineers can check a Building Information Model alongside the design process. Designers should conduct in their BIM authoring platforms some validation phases, such as the Clash Detection one [42]. Nowadays, in fact, the majority of BIM authoring platforms contains tools to perform a preliminary check of the interferences or a partial BIM validation of geometric aspects. That is an important point, since checking the informative contents of a Building Information Model, should be required in many phases, the so-called checkpoints [42], in order to detect in advance any potential issues and guarantee a reliable performance of the following BIM-based analyses. Moreover, the model validation and the analysis of the results should be included in the standard design iterative process and enough time should be allocated for it, including the time required to make any adjustment [17,42].

On the other hand, current BIM design tools do not provide more advanced Model Checking capabilities based on customisable rule sets; that is the reason why dedicated BIM tools are required which apply rules to IFC building model data [38,39]. Improving data interoperability remains a major issue for the communication between different BIM platforms and tools within a BIM environment. [38,39].

3.2. Validation domains

In the proposed case study, IFC models of the various disciplines were exported from Allplan and DDS-CAD and imported in Solibri Model Checker, a commercial application for automatic rule-based checking [24]. During the Model Checking phase, geometrical and alphanumerical information was checked according to various validation domains in order to assure the quality of the proposed design solution. A customised parametric rule set was created and organised in three consequential checking phases [16,43]: BIM Validation, Clash Detection, and Code Checking. Alongside the modelling phase, as well as at the end of it, IFC models were checked for quality, internal consistency, parametric attributes and modelling procedures by the BIM Validation rule set. After that, geometrical interferences were detected, before in individual disciplinary models and later in the federated one. The Code Checking domain was the last step of the validation phase and aimed to check the compliance of the proposed design solution to selected Italian codes and regulations.

3.3. The creation of a customised set of rules

The traditional design validation process, manually performed, is a time-consuming, expensive, and error-prone procedure [38] that requires several meetings and comparisons [44,45]. Rule-based Model Checking, that was defined as one of the major BIM trend for 2015 [19], seems to be actually increasingly needed [19] since it can provide more quickly and reliably validation results in a BIM-based design process [19,38,46]. During the Model Checking phase, the parameters contained in the information models, whether geometric or not, are analysed and validated by testing the Building Information Model through various validation domains [16]. Design evaluation may apply to information requirements, model correctness, constructability, maintenance, and other aspects of the project [38].

In the proposed Pilot Project, Solibri Model Checker was used for an IFC-based rule checking procedure allowing the Public Client to effectively drive the design and construction process and to have a clear idea of the critical issues related to lack of information and possible problems on site. This IFC-based tool contains a library of rules whose parameters can be customised by the user according to their computational complexity and imposed requirements [24]. According to the agreed-upon BIM uses, some of these rules were properly configured and used to create a new rule set through which the various aspects of BIM models were checked.

The created rule set was divided into three checking steps; moreover, these sections were in turn organised into rule sets of lower level, divided by themes and types of control, containing both prescriptive requirements and performance-based regulations translated and transformed into parametric rules [36,47]. Textual rules were also added and they contain references to BIM requirements and Italian

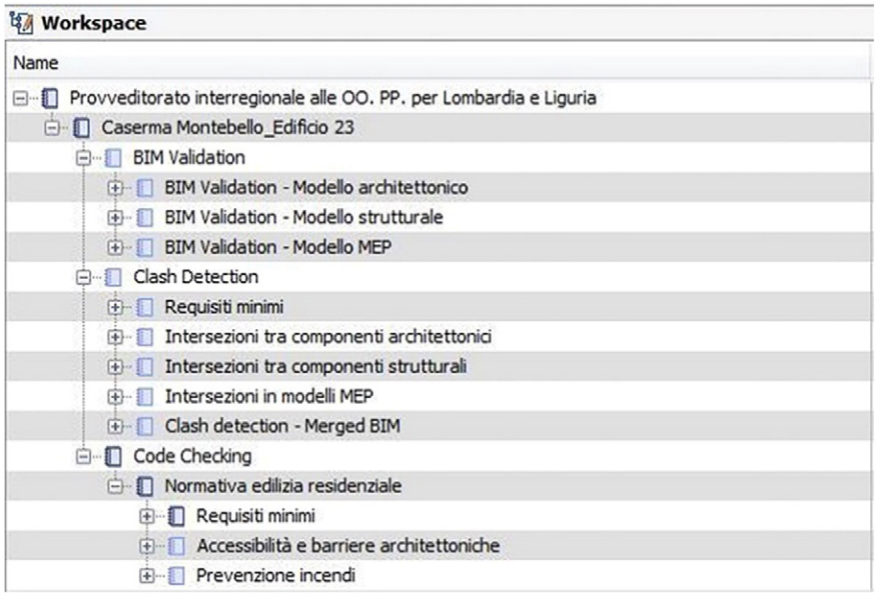

Fig. 1. The rule set is organised in three phases: BIM Validation, Clash Detection, Code Checking.

national codes and regulations (Fig. 1). Titles and description fields were filled in the Italian language in order to facilitate the implementation of the tool for the internal use of the Public Client. BIM validation and Clash Detection rules were enriched with references to the best practises of information modelling and management specified by the Finnish Common BIM requirements 2012 (COBIM 2012). The reference is primarily to Series 1—General Part [48] and Series 6—Quality Assurance [49]. Some rules can be checked either automatically or semi-automatically, while other rules require a manual control [24]. In the latter case, the rule itself represents a sort of reminder for the checking phase [49].

Even if the Clash Detection is one of the most known Model Checking uses, also because of the positive effort–benefit ratio [20], compliance checking is an ongoing trend for building permits [22,50]. In this case, Code Checking rules were implemented by translating in parameters some selected parts of different Italian codes and regulations for residential buildings. The customised set of rules validates very specific problem domains such as compliance to the building code at national and local level, accessibility requirements for residential buildings, and fire safety code for residential underground car parks. Client's requirements were also included [24].

The RASE (Requirement, Applicability, Selection, Exception) methodology was applied to translate the prescriptive requirements of normative text into a computable language [36,51]. The RASE semantic mark-up methodology can be used to efficiently convert qualitative statement in regulations and quantitative metric applicable in rules [36]. The Rule Checking process, in fact, is composed of four major stages [21,24,38]: rule interpretation, building model preparation, rule execution, and rule reporting [24]. Rule interpretation is a key step in the rule checking process in order to convert human-oriented languages into a computable one [24].

3.3.1. BIM Validation

The BIM Validation rule set analyses quality and internal consistency of a Building Information Model. This check guarantees the production of a high-quality Building Information Model from which it is possible to extract any reliable data for further BIM-based analyses [49]. This rule set checks geometrical and non-geometrical attributes embedded in the model in order to validate property values and modelling procedures. For example, BIM Validation rules allow the analysis of the informative content associated to a parametric object and the validation of the correspondent Level of Development (LOD) based on what detailed in the BIM Execution Plan (BEP) [12]. Consider a “Door” element: a specific LOD matches with several attributes such as “Fire rating,” “Fire Exit,” and “Door operation” [12,52] and a BIM Validation rule can check if the parameter exists and how it is filled.

In the proposed case study, BIM Validation rules were divided into three lower level sets to validate the architectural, structural, and MEP disciplinary models. This check was used to identify two types of error, concerning design issues and modelling ones. It was possible to find out, for example, building elements incorrectly located and modelling errors such as wrong constraints of structural elements (Fig. 2). Non-geometrical data were validated, too. For example, it was possible to check if the Activity ID attribute had been added to all the building elements. Moreover, the value of the Activity ID attribute was checked to be the same as the one of the relative construction activity involving the BIM object: this was fundamental for automatically matching the 3D BIM to the construction schedule.

3.3.2. Clash Detection

Clash Detection is a BIM use achieved by means of the best efforts and benefits configuration because it does not necessarily require information-rich objects [30]. Anyway, Solibri Model Checker can be used to validate two different types of data: geometrical data and alphanumerical ones. With this kind of tool, it is possible to talk about Advanced Clash Detection because the detected clashes can be analysed and grouped according to severity [53].

Clash Detection was used to check coordination and collaboration between different design teams at the detail design phase as well as to improve the integration of the main contractor in the decision-making process during the design phase. It was possible to detect clashes between MEP systems and architectural design but, moreover, clashes between MEP systems and structural elements. When the latter case occurs, either openings in structural elements are to be designed or route of MEP systems are to be changed. The aim was to demonstrate that this type of tool, when effectively implemented by a Public Client, could significantly improve the design validation process and avoid errors that, if lately detected, during the construction phase, would lead to additional time and cost.

In order to obtain reliable results from the Clash Detection phase, it is necessary to model according to certain BIM requirements. First of all, it is essential to model with a high degree of geometric accuracy [12,54] in order to avoid conflicts and to identify and correct any problems that might otherwise arise in the phase of installation of MEP systems. In

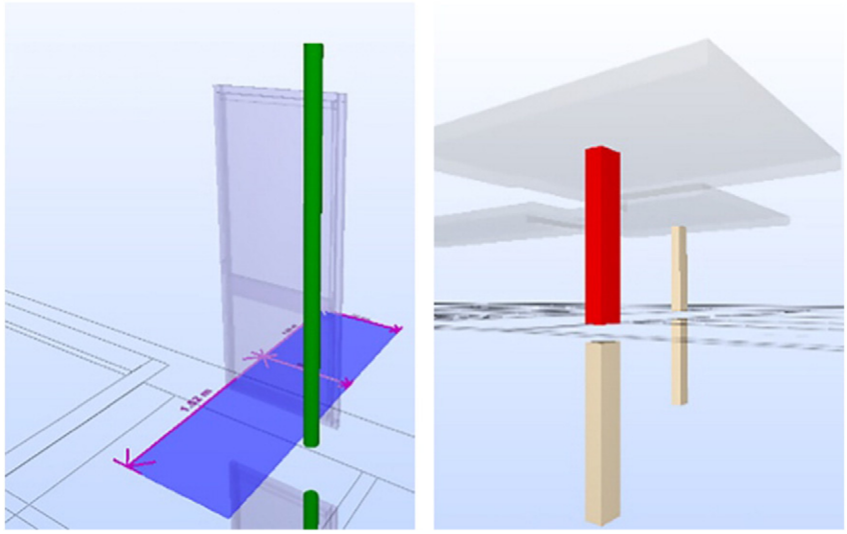

Fig. 2. BIM Validation detects design issues and modelling errors.

this case, the MEP geometric accuracy was such that the installation of MEP components could be easily managed based on the Building Information Model. Parametric rules were set to verify positioning and dimensions of components and any spatial conflict was identified. In order to achieve this purpose, every discipline was internally checked before detecting clashes between different disciplines (Fig. 3). The clearance to install and maintain MEP elements was checked and it was possible to identify, for example, that one of the vertical elements of the sewer system was a size greater than that of the shaft designed for its installation. The geometric accuracy allowed the measurement of the maximum height reached by pipes and ducts where different systems intersect, and it was possible to check, for example, the sizing of screeds for the installation of facilities in flooring (Fig. 4).

In order to avoid errors that would lead to unmanageable results, a reminder to the minimum requirements was added to this rule set. A manual control is required to check that Building Information Models of different disciplines are represented in the same design version. Similarly, coordination and proper localisation of the Cartesian coordinate system have to be checked [49].

3.3.3. Code Checking

Automated Code Checking is a specific case of Model Checking that validates Building Information Models and design requirements comparing the parameters of the information model against current codes and regulations [40]. It is based on the combined use of rules derived from normative requirements at local, national, and international level [51], clients requirements and best practises coming from own experiences [24] with a three-dimensional (3D) and object-based design [55].

In this Pilot Project, the Public Client wanted to check the BIM-based design against some sections of the residential building code at a local level and the Italian fire prevention code for residential underground car parks. As already mentioned in Section 3.1, normative texts were translated into a computable language by the use of the RASE markup methodology [50]. The created Code Checking rule set was enriched with the Italian description of all the normative references. IFC models and their parametric attributes were managed with the necessary classifications. Once the regulations had been translated in parameters and implemented into parametric rules, semi-automatic Code Checking was used to evaluate the project and to provide a rapid analysis of issues for every single object contained in the BIM, otherwise the sampling analysis traditionally conducted on 2D CAD drawings. Attributes of every single BIM object were checked, both the geometrical and alphanumerical ones, and it was evident that requirements of a rule checker for building models were stricter than existing 2D drawings. The reason is that the needed data are not automatically generated by BIM authoring platforms, as it occurs for geometric information and dimensional attributes [12,56].

Preliminary BIM Validation and Clash Detection guaranteed reliable results for the Code Checking phase.

- Requirements of residential buildings

IFC space objects were classified according to the typologies specified in the normative text. Classification rules were implemented in order to automatically manage the information contained in the IFC

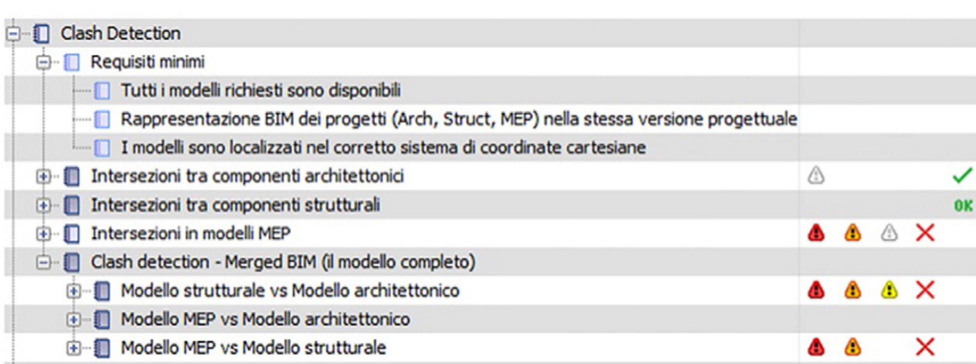

Fig. 3. Clash Detection checks the coordination between different design teams.

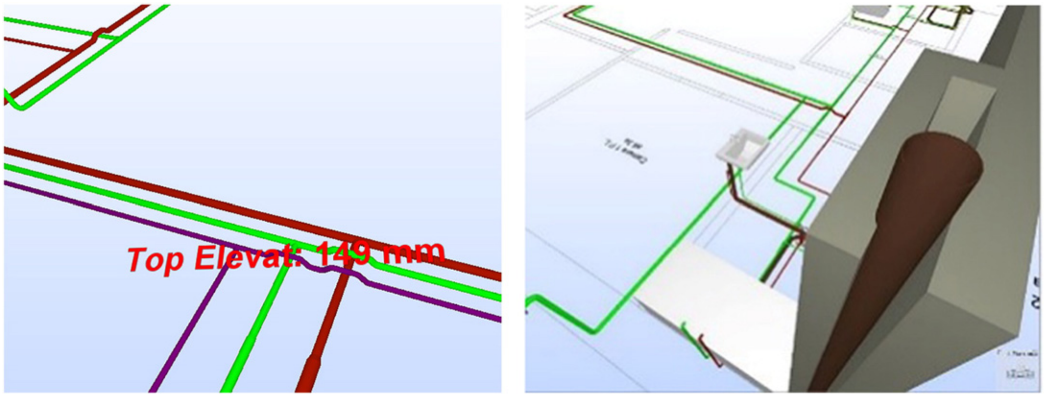

Fig. 4. High degree of geometric accuracy in modelling MEP systems allowed the team to identify any potential issue.

models. In this way, every time an IFC model was updated, the classification was automatically updated, too.

First of all, Code Checking dealt with geometrical aspects. For example, rules were set to validate the minimal surface of bedrooms, distinguishing between those with one or two beds. The same type of check was applied to other spaces of the apartments such as living rooms, kitchens, toilet rooms, and circulation spaces. Similarly, volumes and minimum heights of spaces were checked. Other checks were carried out on issues such as lighting and ventilation: by analysing the information contained in the IFC models, it has been possible to check the window-to-floor ratio and to identify, inter alia, toilets with no windows for which a further check for mechanical ventilation requirements was required. Communication between spaces was also validated. For example, it was checked that direct access to a space named “toilet” was possible only from a space named “corridor” or “hallway” and classified as “circulation” rather than directly from other spaces where people stay [31]. The design of stairs, modelled as parametric components, was also subjected to Code Checking (Fig. 5). The conformity of design parameters was checked, such as minimum width of the ramp, minimum space for access to the ramp, minimum size of landings, maximum number of steps in a ramp, and the sum of two risers and one tread. Settings were also differentiated in order to control both internal and external stairs appropriately classified.

- Accessibility rules

Accessibility represents a crucial design issue and a detailed set of factors not easy to be interpreted. To date, geometrical requirements have been checked such as the ones related to manoeuvring space of the wheelchair (Fig. 6). On the next future, it would be possible to go further by including also sensorial aspects as the presence of tactile (haptic) signals, the effort needed to open doors and windows, the use of colours, light, and noise conditions [12,57]. To this end, a demanding building model preparation would be required. In Italy and internationally, Code Checking is addressed to this direction [21,57]. Moreover, the theme of the accessibility in the validation of design has been already investigating with the use of immersive environments [58].

- Fire prevention

Fire prevention and egress analysis rules were implemented in order to check fire compartments and communication to emergency exits. Fire prevention rules depend on the parameters of the project, the

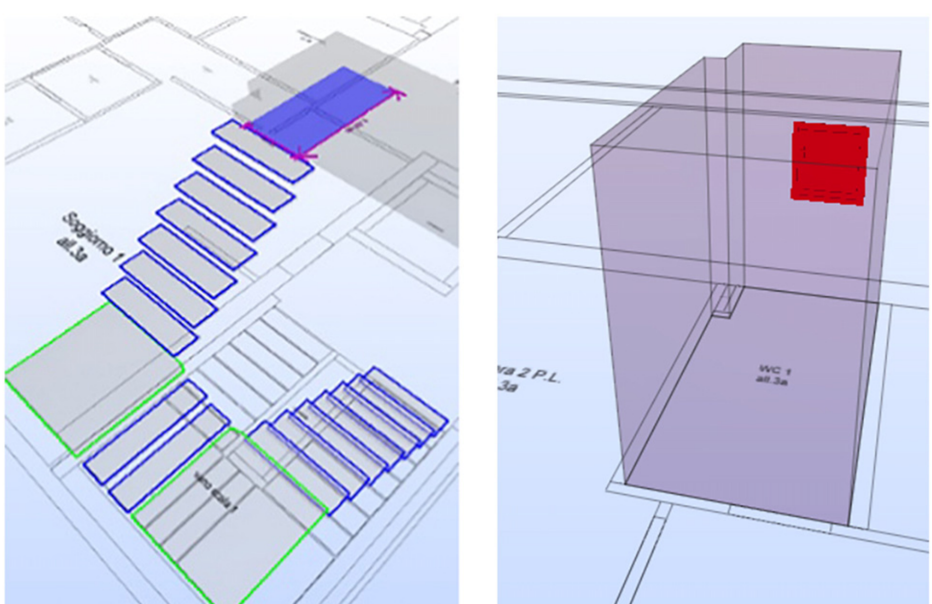

Fig. 5. Residential building code automatically checked by use of a customised rule set.

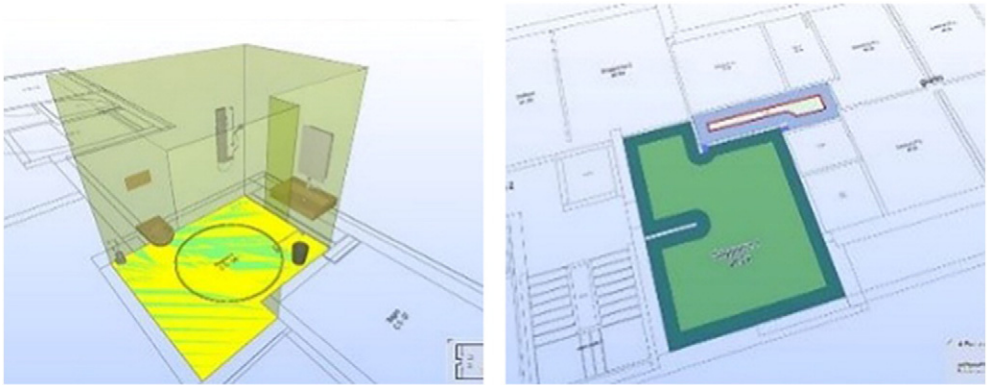

Fig. 6. The accessibility rule set checks the manoeuvring space of the wheelchair.

location, and the type of building [49]. Moreover, rules provide results that are based on the information available within the BIM model. Such an information could be inaccurate or false, causing the generation of unreliable results. For this reason, all parameters must be carefully checked with a preliminary BIM Validation. The necessary classification of data and the compartmentation view are to be configured. For example, emergency exits, which represent a fundamental information for egress analysis, are to be manual classified if they are not correctly specified in the BIM authoring tool. Meanwhile, fire prevention checking can be automated if necessary BIM objects and requirements are correctly embedded in the IFC model; in this case, it was done during the Building Model Preparation phase.

Alphanumeric attributes, such as the fire resistance one, were defined for structural and architectural elements such as walls, columns, and doors directly within the Building Information Models. Direction of openings and panic handles were defined for fire doors. If these parameters are embedded in the BIM, the Model Checking software can read them directly from the IFC model as well as it reads dimensional geometric attributes of the objects themselves and automatism can be achieved. Fire safety attributes were linked to the model in Microsoft Excel thanks to the possibility to manage Allplan native data by using a spreadsheet. During the BIM validation phase, it was checked that these attributes had been added that the property values were correct. For example, it was checked that the attribute of fire resistance "resistenza al fuoco – REI 120" had been defined for every wall, column, and door that divided the car park into fire compartments. REI 120 is the fire rating according to the Italian code for not sprinklered underground car parks. The car park was automatically apportioned in fire compartments by architectural and structural elements for which the fire resistance parameter had been defined as REI 120 (Fig. 7). Property values of the Italian standards were set to check properties of fire compartments, such as the maximum area according to the type of compartment in residential buildings not equipped with a sprinkler system. It was checked that doors classified as "emergency exit" isolated smoke proof stairs and their size was in accordance with the minimum size requirements for escape routes depending on crowding density and flow capacity. It was verified that paths not longer than 40 m were necessary to arrive at emergency exits. To this purpose, in order to allow a reliable analysis, all ancillary and MEP rooms were set as "restricted" and the path through them was not taken into account during the check. Rules checked components classified as fire protecting components: properties of the fire piping system, location and number of fire prevention devices were checked. Hydrants were checked for presence at each exit, as required by the regulations. The same control concerned the presence in sufficient numbers of fire extinguishers, the distance from each other and their positioning with respect to emergency doors (Fig. 8).

This section of the rule set does not cover the entire aspects of the analysis of escape routes. A manual control is necessary in reference to current regulations [47,49].

4. 4D Building Information Modelling

4.1. Traditional approach to construction management

Construction planning is the crucial driver to ensure the success of a project. Without construction management, in fact, it is likely not to achieve project objectives, in terms of cost, time, and resources usage. Construction scheduling is an iterative process done in consequential phases and with increasing levels of detail. The construction schedule constitutes the point of reference against which to calculate deviations and identify corrective actions as the construction progresses. To date, the burden of scheduling construction activities is, almost exclusively, of the project planner. In fact, the validity of the construction schedule is mainly a function of his experience as there is no database to refer to gather the necessary information. This implies a high probability of making mistakes even for the most experienced planner, especially when there is not a strong collaboration with other actors of the process [59]. In fact, the project planner is often required to know construction techniques, logical links between various activities and the time required to complete tasks without having the necessary relationship with designers and sometimes not fully knowing the actual availability

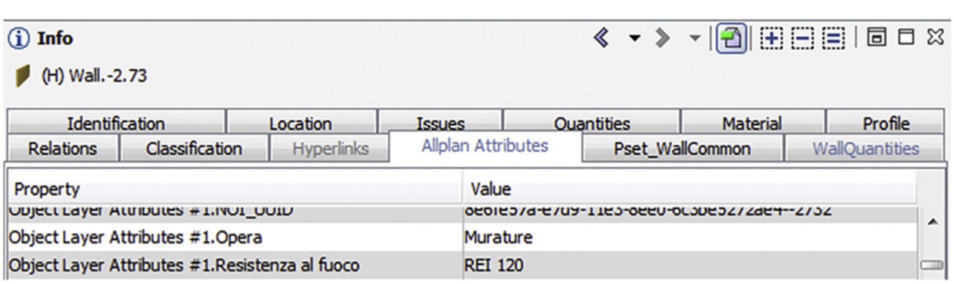

Fig. 7. Fire safety BIM attributes were added to the Building Information Model.

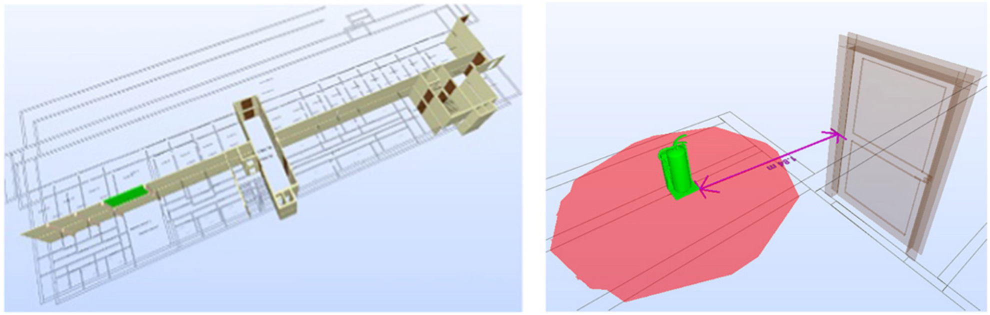

Fig. 8. Fire prevention rules automatically checks fire compartments and fire equipment location.

of resources of the construction company. Often the tendency to work in a piecemeal way leads to realise a not adequate construction schedule that distorts the prediction of the construction progress, leading to delays and other problems that are detected only during the construction phase, when the necessary corrective actions are expensive and little effective [47,60]. Another lack of the traditional process lies with the ability to visualise and to correctly understand the relationships occurring between different activities, including possible errors in the choice of these constraints. Typically, the construction site is represented with two-dimensional static CAD drawings that are disconnected from the time schedule [61]. This makes it difficult to understand the evolution of the construction site layout in relation to the construction progress. It requires to mentally reconstruct all that will happen in the construction site and to merge the scheduled work packages with what is represented in traditional 2D layouts. They often have not comparable levels of detail: detailed work packages versus macro-phases representations. Material storage spaces represent another aspect affected by this lack of connection between construction schedule and construction site layout. In fact, the designated storage areas are displayed only in front of macro construction phases, but they are not connected with the supply plan and so it is not possible to verify if these prove adequate. Moreover, only a few of the construction vehicles that will be used are indicated and this could lead to an inaccurate analysis of their suitability and manoeuvring areas.

4.2. Proposed methodology

Synchro PRO was used for 4D Modelling and project scheduling. Synchro PRO is an IFC-based tool for construction management. It can both import and export IFC models and, in the latter case, they are enriched with Synchro attributes added from the contractors. Moreover, in this tool, it is possible to create a schedule by means of an interface similar to the one of Primavera Project Management.

A 4D BIM was created by linking all the elements of the Building Information Model to the construction schedule in order to visualise and optimise the construction sequences [62]. A 4D BIM helps to solve some typical deficiencies of the traditional approach and to better schedule the project. A virtual construction site can be built and issues usually detected during the construction phase can be anticipated [19]. In this way, the construction site can be visualised by the actors involved so they do not have to imagine what would happen during the construction phase. In recent years, the construction scheduling process has been more and more supported by 4D Modelling tools but at present this kind of technology is not yet widespread as an integral part of the construction process [25,63].

In order to correctly configure the 4D BIM, it is necessary to decide how to proceed during both the modelling phase and the construction scheduling one. BIM requirements necessary for 4D BIM significantly affects the way the BIM model is to be created as well as the scheduling of the construction plan. It is fundamental to define the granularity of both 3D model and construction schedule in order to successfully link the elements of the PBS (Product Breakdown Structure) to the WBS (Work Breakdown Structure) work packages. If the granularity of BIM and construction plan is not the same, two different situations may occur [26]: either the BIM granularity is higher than the one of the construction schedule, or vice versa, the BIM granularity is lower than the WBS one. The former case does not represent a problem since it is possible to gather more BIM objects and to link them to a single work package. On the contrary, the latter case represents a critical issue because it is necessary to link a single building element to a multiplicity of work packages. A compromise is needed: the BIM object can either be linked to only one of the work packages composing a WBS element or it can be linked to every work packages, and so counted more times. The former solution does not allow the visualisation of the execution of different work packages in the 4D model. In the latter case, resources are allocated in a wrong way because the element would be built or removed again and again.

In this case, for a BIM granularity lower than the one of the construction schedule, some customised colour schemes were used in order to represent the incompleteness of the element until the conclusion of the chronologically last work package.

Once the WBS levels had been identified, work packages were defined and associated to the elements of the PBS. Resources and construction techniques were defined as well as duration for each activity. Logical links between the planned activities were assumed. Firstly, it was necessary to add construction objects to the Building Information Model. The target of the 4D model, in fact, imposes what is to be modelled and which activities should be defined in the construction schedule. For example, a 4D BIM that has as its purpose the validation of the security plan requires safety and temporary devices, such as scaffolds and formworks, to be modelled. The same is for construction vehicles. At the same time, the construction schedule has to be more detailed than in the traditional planning practise. It has to contain activities that are not usually covered, such as the ones involving the displacement of the storage areas.

The construction site layout was modelled in Allplan. Construction site offices, accesses, fences, and temporary ramps were modelled. For obtaining a complete overview, surrounding buildings were also modelled as masses. A mock-up of the procedures of formworks construction, concrete casting and formwork removal was modelled, including temporary equipment such as scaffolds (Fig. 9). In order to ensure the auto-matching between the 3D BIM model and the construction schedule, a parameter, named Activity ID, was associated to each element by exporting the Building Information Models in an Excel spreadsheet. At the same time, the construction schedule was also extracted from Synchro PRO and imported into Excel. From that spreadsheet the Activity ID of the various activities of the construction schedule was selected and reported in the model database, filling the corresponding attributes previously added to the relative BIM objects. In this way, construction activities and parametric objects were characterised by the same Activity ID and it was possible to filter the Building Information Model in function of various construction phases. The updated database was imported back into the BIM authoring platform and an updated IFC model was extracted to be imported in

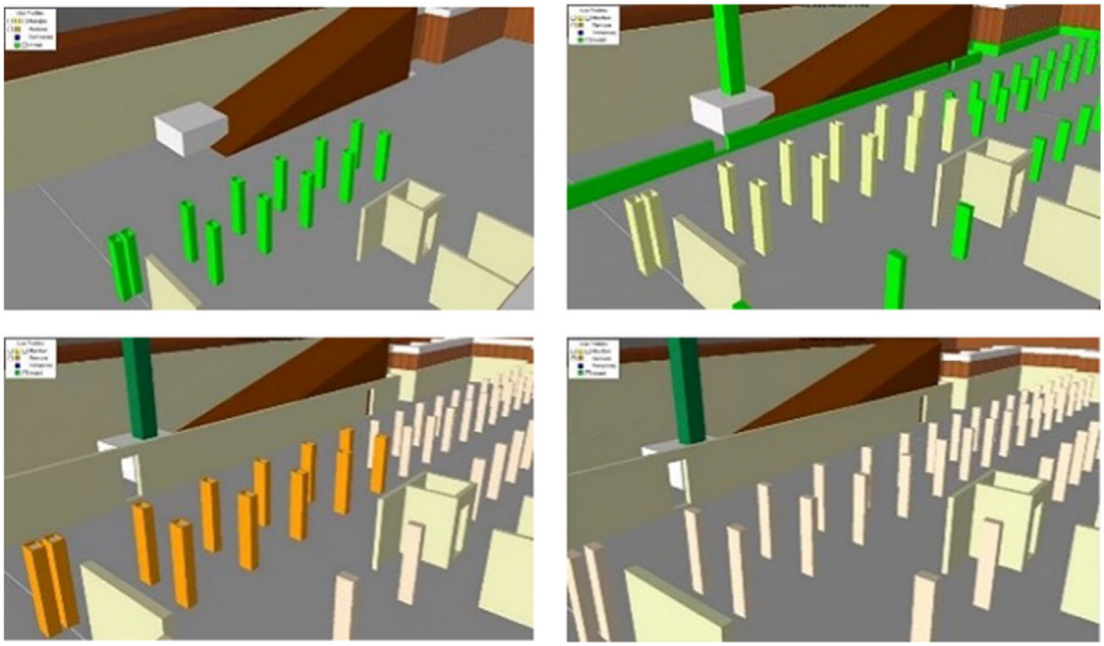

Fig. 9. Procedure of construction of concrete formwork, concrete casting, and formwork removal of the basement columns.

Synchro PRO. In the 4D BIM tool, it was possible to configure an auto-matching rule [64], linking each object to the relative construction activity according to the value of the Activity ID. Once verified that the proposed association automatically provided as result of the auto-matching rule was correct, it was indicated whether the item should had been created, removed, or retained. Finally, the machinery needed to complete the works were defined. The 3D model of these resources was selected from the internal object library of Synchro.

5. IFC-based joint use of Model Checking and 4D BIM

During the described Pilot Project, IFC-based tool for Model Checking and 4D modelling were used. Moreover, Synchro PRO allowed the extraction of IFC models that are representative of different construction site configurations. This possibility was used to set up some validation tests and data analyses related to the construction phase.

It is interesting the possibility to compare IFC models extracted from the 4D BIM tool, and related to different days of the construction phase, in order to monitor the construction progress and see what is added from a configuration to another one (Fig. 10) alongside construction progresses and time passes. The Information Take-off tool of Solibri was tested to be used to monitor the percentage of completion of the construction progress. Moreover, the as-built model could be verified by comparison to the original baseline of the construction schedule.

The joint use of Model Checking and 4D BIM could be also tested to support the Health and Safety management by adding devices and temporary equipment to the model and integrating the schedule with specific activities related to their placement on the construction site. In particular, construction site configurations in critical days could be extracted as IFC models from the 4D BIM analysis in order to be validated by an appropriate Health and Safety rule set [38]. Obviously, this goal would require the integration of the Building Information Model with data from a variety of construction safety documents, moving from a paper-based process to a digitalised one.

6. Results and discussion

The Pilot Project involved all the stakeholders and allowed them to face with the new methodology and technology related to a digitalised building process. The Model Checking phase allowed the Public Client to effectively validate the design and avoid issues that had not been detected in the previous manual and traditional process. The implementation of a 4D BIM tool helped the main contractor to optimise the construction phase, but above all it made it clear to the Public Client the possibility to actively control and manage also this phase.

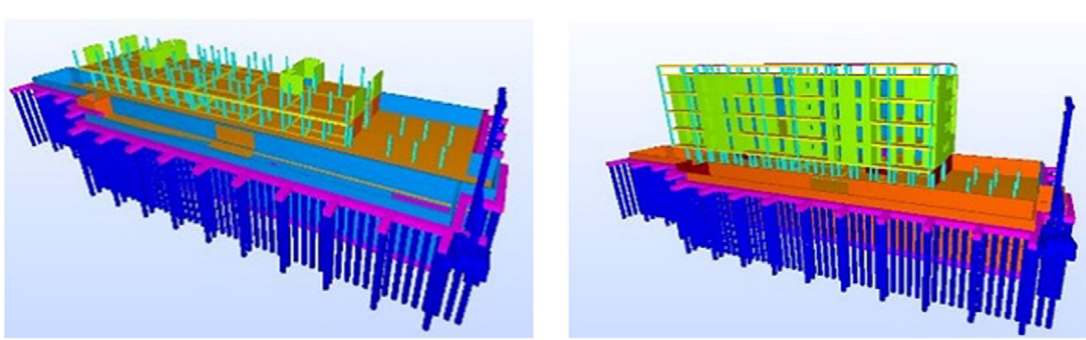

Fig. 10. Construction progress Information Takeoff based on the IFC models exported from the 4D BIM tool.

6.1. Model checking results

Model Checking as an iterative process allowed design optimisation and a consistent data flow between project participants. Design issues detected during the Model Checking phase were shared in coordination meetings during the rule reporting phase with all the actors involved in the experimentation.

The aim was to help the Public Client to understand that this type of tool, if effectively implemented into the building process, could significantly support clients and designers to improve the design validation phase and avoid errors that, if lately detected, during the construction phase, would lead to additional time and cost [47,60]. Critical issues, which had not been detected manually in the previous traditional process, were reported to the Head of the Department who asked for a more thorough check of the building design and for corrective actions to be taken before the construction phase started. Designers had to modify their design solutions according to the Model Checking results.

6.2. Achievements of 4D Building Information Modelling

Throughout the 4D BIM, it was possible to visualise the construction sequences (Fig. 11). This methodology enabled the team to validate the schedule and to identify errors in the logical link between activities. Once the macro errors had been resolved, it was possible to introduce some specific analyses. First of all, improving variations were analysed by comparing different baselines that would allow a reduction of the necessary time for completing the construction works. Every new baseline was compared with the original one considering advantages and disadvantages. In particular, alternatives that, compared to a reduction of the time, would not have compromised the safety of workers were sought. For example, baselines that included simultaneous tasks to be concurrently performed by different subcontractors in the same area were excluded. Synchro PRO allowed this comparison and the simultaneous viewing of the evolution of the construction site according to different baselines. The best construction schedule was defined through an iterative comparative process and subsequent correction of the baseline proposal.

The construction site was affected by a lack of space and coordination problems. 4D BIM was used to compare different alternatives for positioning the tower crane in order to optimise the layout of this confined construction site. The best solution was defined in collaboration with the main contractor. The impact of traffic due to the construction activities on the dense urban district and a detailed analysis of the access to the construction site was performed. An alternative solution to the original one was identified to reduce to a minimum the inconveniences caused by the construction site.

7. Conclusions

The case study, describing the first Italian official attempt to implement Building Information Modelling by a Public Client Organisation, allowed the research unit to realise how the constraining rules built into the Italian contractual frameworks (in spite of the EU Directives' transposition) could vanish the potential benefits offered by digitised routes. Moreover, the simulated entire design and construction management processes emphasised the ineffectiveness due to a silo approach shared by all the Stakeholders over the construction process. Notwithstanding the numerous advantages of this innovative methodology, some cultural hindrances hampered the original features of the Information Modelling and Management process. Initially, all the Project Stakeholders demonstrated some kind of reluctance in coordinating their own work and in collaborating in order to effectively implement BIM in the detailed design and construction phase of the residential building.

Such an interoperable and collaborative approach still needs to be tailored to a selfish and silo mindset. The simulated workflows should

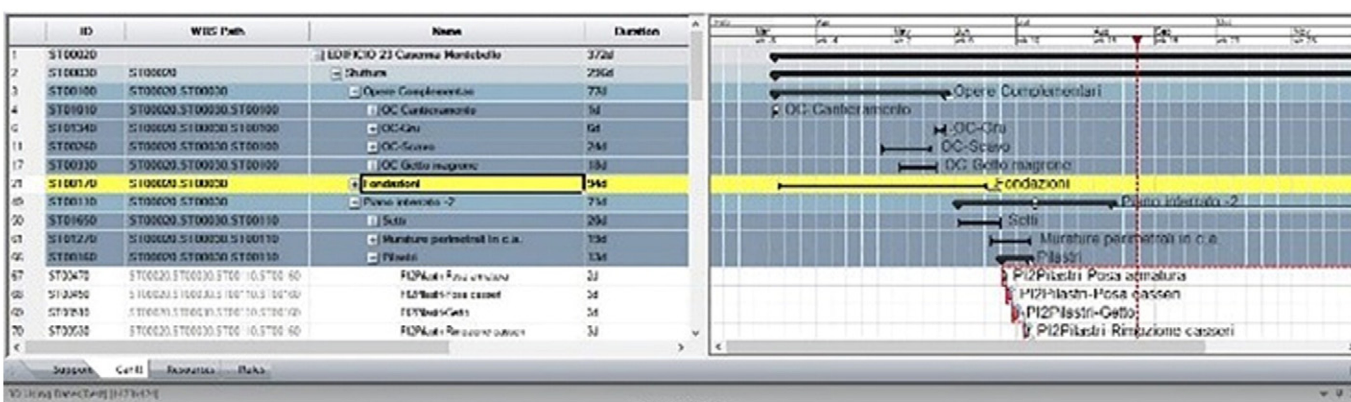

Fig. 11. Visualisation of the construction schedule in Synchro PRO.

be enabled and introduced according to a customised criterion, taking into account a long-termed transition. In order to obtain these results, the collaboration between owners, design teams and contractors has to be significantly improved.

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References

[1] M. Bolpagni, The Implementation of BIM within the Public Procurement. A Model-Based Approach for the Construction Industry, VTT Technology, 2013 (http://buildingsmart.no/sites/buildingsmart.no/files/2014_vtt_sf_marzia_bolpagni_bim-procurement.pdf).
[2] Construction Manager, BIM around the World – Country by Country, http://www.construction-manager.co.uk/agenda/bim-around-world-country-country/2015.
[3] E. Di Giacomo, BIM Trends from all around the World, European BIM Summit, http://numerique.tech.fr/Barcelona_BIM_Summit_Feb_13th_EDG150213_P.pdf2015.
[4] Office Journal of the European Union, Directive 2014/24/EU of the European Parliament and of the Council of 26 February 2014 on Public Procurement and repealing Directive 2014/18/EC, Article 22(4), Volume 57, Publication office of the European Union, (March 28 2014)
[5] BIM Task Group, A UK Government Initiative, http://www.bimtaskgroup.org/
[6] AEC (UK), BIM Technology Protocol v2.1, https://aecuk.files.wordpress.com/2015/06/aecukbimtechnologyprotocol-v2-1-1-201506022.pdf2015.
[7] Digitales bauen, http://www.digitales-bauen.de/
[8] ZukunftBAU, A research program of the Federal Ministry for Transport, Building and Urban Affairs (BMVBS), Federal Republic of Germany, 2013 (http://www.aec3.com/de/downloads/BIM-Guide-Germany.pdf).
[9] B. Delcambre, Mission Numérique Bâtiment, http://www.territoires.gouv.fr/IMG/pdf/rapport_mission_numerique_batiment.pdf2014.
[10] E. Knutt, Spain launches BIM strategy with pencilled-in 2018 mandate, http://www.bimplus.co.uk/news/spain-launches-bim-strategy-pencilled-2018-mandate/2015.
[11] BuildingSMART Spain, http://www.buildingsmart.es/
[12] A. Ciribini, S. Mastrolembo Ventura, M. Bolpagni, Informative content validation is the key to success in a BIM-based project, Territ. Italia 2 (2015) 9–29, http://dx.doi.org/10.14609/Ti_2_15_1e.
[13] SmartMarket Report, McGraw Hill Construction, the business value of BIM for owners, http://i2sl.org/elibrary/documents/Business_Value_of_BIM_for_Owners_SMR_%282014%29.pdf2014.
[14] SmartMarket Report, Dodge Data & Analytics, measuring the impact of BIM on complex buildings, https://c.ymcdn.com/sites/www.nibs.org/resource/resmgr/Docs/BIMSmartMarketReport.pdf2015.
[15] J.L. Salmon, Wicked IPD procurement programs: IPD & BIM solutions unleashed. Autodesk user group international (AUGI), https://www.augi.com/library/wicked-ipd-procurement-programs-ipd-bim-solutions-unleashed2012.
[16] B. Dave, S. Boddy, L. Koskela, Challenges and opportunities in implementing Lean and BIM on an infrastructure project, in: C.T. Formoso, P. Tzortzopoulos (Eds.), 21st Annual Conference of the International Group for Lean construction 2013, pp. 741–750.
[17] Cabinet Office, Government Construction Strategy: Trial Projects, https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/62628/Trial-Projects-July-2012.pdf2012.
[18] AIA, Integrated Project Delivery, A Working Definition, https://www.dir.ca.gov/das/hcc/WorkingDefinition.pdf2007.
[19] C. Eastman, P. Teicholz, R. Sacks, K. Liston, BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors, second ed. John Wiley & Son Inc., USA, 2011.
[20] A. Ciribini, M. Bolpagni, E. Oliveri, An innovative approach to e-public tendering based on Model Checking, Proceedings of the8th Nordic Conference on Construction Economics and Organization, 2015http://dx.doi.org/10.1016/S2212–5671(15)00147–1.
[21] C. Eastman, J. Lee, Y. Jeong, L. Lee, Automatic rule-based checking of building designs, Autom. Constr. 18 (8) (2009) 1011–1033, http://dx.doi.org/10.1016/j.autcon.2009.07.002.
[22] S. Malsane, J. Matthews, S. Lockley, P.E.D. Love, D. Greenwood, Development of an object model for automated compliance checking, Autom. Constr. 49 (2015) 51–58 (part A). http://doi.org/10.1016/j.autcon.2014.10.004.
[23] J. Dimyadi, R. Amor, Automated building code compliance checking – where is it at? Proceedings of the 19th CIB World Building Congress 2013, pp. 172–185 (http://hdl.handle.net/2292/23574).
[24] W. Solihin, C. Eastman, Classification of rules for automated BIM rule checking development, Autom. Constr. 53 (2015) 69–82 http://doi.org/10.1016/j.autcon.2015.03.003.
[25] C. Boton, S. Kubicki, G. Halin, The challenge of level of development in 4D/BIM simulation across AEC project lifecycle, Procedia Eng. 123 (2015) 59–67, http://dx.doi.org/10.1016/j.proeng.2015.10.058.
[26] T. Hartmann, J. Gao, M. Fisher, Areas of application for 3D and 4D model on construction projects, J. Constr. Eng. Manag. 134 (10) (2008) 776–785, http://dx.doi.org/10.1061/(ASCE)0733–9364(2008)134:10(776.
[27] J. Turke, J. Hanff, 4D Construction sequence planning: new process and data model, Proceedings of the 24th CIB-W78 conference on Information Technology in Construction, 2007.
[28] HM Government, Trial project: Cookham Wood, https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/325950/Cookham_Wood_case_study__CE_format__130614.pdf
[29] Statsbygg BIM Manual 1.2.1, http://www.statsbygg.no/Files/publikasjoner/manualer/StatsbyggBIM-manual-ver1-2-1eng-2013-12-17.pdf
[30] AGC of America, The Contractor's Guide to BIM, second ed., 2010.
[31] J.M. Lee, Automated Checking of Building Requirements of Circulation Over a Range of Design Phases, Georgia Institute of Technology, 2010https://smartech.gatech.edu/bitstream/handle/1853/34802/lee_jae_m_201008_phd.pdf?sequence=1.
[32] The British Standard Institution, PAS 1192–2:2013 Specification for information management for the capital/delivery phase of construction projects using building information modelling, http://www.bimtaskgroup.org/pas11922-overview/
[33] GSA, 3D-4D Building Information Modeling, http://www.gsa.gov/portal/category/21062
[34] R.G. Kreider, J.I. Messner, The Uses of BIM: Classifying and Selecting BIM Uses, Version 0.9, The Pennsylvania State University, University Park, PA, USA, 2013 http://bim.psu.edu.
[35] BIMForum, LOD Specification, https://bimforum.org/lod/
[36] E. Hjelseth, Foundation for development of computable rules, Proceedings of CIB-W78 Conference 2009, pp. 1–10.
[37] P. Sanguinetti, S. Abdelmohsen, J. Lee, H. Sheward, C. Eastman, General system architecture for BIM: an integrated approach for design and analysis, Adv. Eng. Inform. 26 (issue 2) (2012) 317–333, http://dx.doi.org/10.1016/j.aei.2011.12.001.
[38] S. Zhang, J. Teizer, J.K. Lee, C. Eastman, M. Venugopal, Building information modeling (BIM) and safety: automatic safety checking of Construction models and schedules, Autom. Constr. 29 (2013) 183–195 http://doi.org/10.1016/j.autcon.2012.05.006.
[39] B. Koo, M. Fischer, Feasibility study of 4D CAD in commercial construction, J. Constr. Eng. Manag. 126 (4) (2000) 251–260, http://dx.doi.org/10.1061/(ASCE)0733–9364(2000)126:4(251).
[40] E. Hjelseth, N. Nisbet, Exploring semantic based model checking, Proceedings of the CIB-W78, 27th International Conference, 2010.
[41] N. Nawari, BIM-model checking in building design, Structures Congress 2012, pp. 941–952, http://dx.doi.org/10.1061/9780784412367.084.
[42] H. Kulusjärvi, Common BIM Requirements 2012 – Series 6 Quality Assurance, buildingSMART Finland, http://files.kotisivukone.com/en.buildingsmart.kotisivukone.com/COBIM2012/cobim_6_quality_assurance_v1.pdf2012.
[43] L. Khemlani, Solibri Model Checker, AECbytes. http://www.aecbytes.com/review/2009/SolibriModelChecker.html
[44] T. Nguyen, J. Kim, Building code compliance using BIM technology, Proceedings of the 2011 Winter Simulation Conference, 2011.
[45] D. Greenwood, S. Lockley, S. Malsane, J. Matthews, Automated compliance checking using building information models, The Construction, Building and Real Estate Research Conference of the Royal Institution of Chartered Surveyours, RICS, London, 2010http://nrl.northumbria.ac.uk/id/eprint/6955.
[46] L. Ding, R. Drogemuller, M. Rosenman, D. Marchant, J. Gero, Automating code checking for building designs – DesignCheck, Clients Driving Innovation: Moving Ideas into Practice 2000, pp. 1–16 (http://ro.uow.edu.au/engpapers/4842/).
[47] E. Hjelseth, Converting performance based regulations into computable rules in BIM based model checking software. In: Architecture, Engineering and Construction – Gudnason & Scherer, Taylor & Francis Group, London, ISBN 978–0-415-62128-1, 2012, 461–469
[48] BuildingSMART Finland, Gravicon Oy, Tomi Henttinen, Common BIM Requirements 2012 – Series 1, General part, https://asiakas.kotisivukone.com/files/en.buildingsmart.kotisivukone.com/COBIM2012/cobim_1_general_requirements_v1.pdf
[49] BuildingSMART Finland, Solibri Inc., Heikki Kulusjärvi, Common BIM Requirements 2012 - Series 6, Quality Assurance, https://asiakas.kotisivukone.com/files/en.buildingsmart.kotisivukone.com/COBIM2012/cobim_6_quality_assurance_v1.pdf
[50] 'BIM for building regs' software plug-ins could be launched by October, http://www.bimplus.co.uk/news/bim-bu2ilding-re3gs-soft4ware-plug-ins/
[51] E. Hjelseth, N. Nisbet, Capturing normative constraints by use of the semantic mark-up RASE methodology, Proceedings of the CIB W78-W102 International Conference 2010, pp. 1–10.
[52] Solibri, Inc. Solibri Snapshot Video: Level of Development (LOD) checking. https://www.youtube.com/watch?v=NNyePtN9J6I
[53] Solibri, Inc. Solibri Snapshot Video: Second Generation Clash Detection. https://www.youtube.com/watch?v=EOJgVOD-fzU
[54] T. Järvinen, T. Laine, K. Kaleva, K. Heljomaa, Common BIM Requirements 2012 – Series 4 MEP Design, buildingSMART Finland, https://asiakas.kotisivukone.com/files/en.buildingsmart.kotisivukone.com/COBIM2012/cobim_4_mep_design_v1.pdf2012.
[55] S. Zhang, J. Teizer, J. Lee, C.M. Eastman, M. Venugopal, Building information modeling (BIM) and safety: automatic safety checking of Construction models and schedules, Autom. Constr. 29 (2013) 183–195, http://dx.doi.org/10.1016/j.autcon.2012.05.006.
[56] R.A. Njiemeijer, B. De Vriès, J. Beetz, Check-mate: automatic constraint checking of IFC models, Managing IT in Construction/Managing Construction for Tomorrow, CRC Press, London 2009, pp. 479–486.
[57] G. Bellomo, BIM and model checking serving people with disabilities, Solibri Magazine, 2012.

[58] T. Hilfert, M. König, Low-cost virtual reality environment for engineering and construction, Proceedings of the 32nd International Symposium on Automation and Robotics in Construction and Mining (ISARC 2015) 2015, pp. 154–161.
[59] V. Popov, V. Juocevicius, D. Migilinskas, L. Ustinovichius, S. Mikalauskas, The use of a virtual building design and construction model for developing an effective project concept in 5D environment, Autom. Constr. 19 (2010) 357–367, http://dx.doi.org/10.1016/j.autcon.2009.12.005.
[60] SmartMarket Report, McGraw Hill Construction, The business value of BIM in North America, multi-year trend analysis and user ratings (2007–2012), http://static-dc.autodesk.net/content/dam/autodesk/www/solutions/building-information-modeling/bim-value/mhc-business-value-of-bim-in-north-america.pdf2007.
[61] M. Fischer, J. Haymaker, K. Liston, in: Ian Flood, Raja R.A. Issa, William J. O'Brien, Taylor & Francis (Eds.),Benefits of 3D and 4D Models for Facility Managers and AEC Service Providers, 4D CAD and Visualization in Construction: Developments and Applications, 2003http://dx.doi.org/10.1201/9780203971123.ch1 (Print ISBN: 978-90-5809-354-7, eBook ISBN: 978–0-203-97112-3).
[62] U.S. General Services Administration Public Buildings Service Office of the Design & Construction, BIM guide for 4D phasing, GSA BIM guide series 04. http://www.gsa.gov/bim
[63] SmartMarket Report, McGraw Hill Construction, Building Information Modeling (BIM), Transforming design and construction to achieve greater industry productivity, http://www.aia.org/aiaucmp/groups/aia/documents/pdf/aias077483.pdf
[64] Synchro Software Level 4 Advanced PRO Training https://synchroltd.com/training/