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The challenge of level of development in 4D/BIM simulation across AEC project lifecyle. A case study.

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Abstract

4D modeling has been an applied research area for around two decades since the first seminal works in the nineties. In the last years, a number of case studies have been published both for demonstrating the various applications of 4D and for assessing technological propositions. However, in most papers only little place is given to the particular content of 4D models. In parallel, following the growing implementation of Building Information Modeling, 4D modeling process is usually recognized as a “BIM use”. In BIM implementations and protocols, the Level Of Development of datasets is a fundamental issue. This paper describes the application of two distinct “4D uses” conducted on a single pilot project. They aim to assess the levels of graphical and temporal details required for the implemented uses. The authors finally discuss the diversity of 4D uses with 4D models, both planned or ad-hoc, as well as the logical understanding related to 4D LOD.

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1. Introduction

4D simulation consists in linking construction activities in a planning to 3D objects in a building model in order to simulate the construction process over time. 4D simulations can be developed at different stages of a construction project to analyze the design and its constructability, as well as for construction planning and monitoring [1, 2]. The

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"4D simulation" concept was introduced before the advent of Building Information Modeling (BIM) [3] but gained from the development of BIM's three-dimensional models. BIM is a recent approach to object-oriented modeling and integration of multi-dimensional construction data. In the last years it is also more and more related to efficiency and quality of digital information exchanges fostering collaboration between construction practitioners.

It could be mentioned that the adoption rate of 4D simulation by construction practitioners remains low [4–6]. Although it is increasingly used in wide-scale or very specific building/engineering projects, there are quite a few feedbacks from experiments on regular projects. One must say that it is a young technology that still has to be adapted to the real business needs [7]. In particular, if 4D modeling fits with traditional Anglo-Saxon approaches to project management, it is not exactly the case in the French nor Luxembourgish construction management culture. One important issue is related to the level of detail (LOD) of the information comprised in Building Information Models, which should fit to the expected 4D usage(s) performed by practitioners. This is a particularly complex issue because 4D simulations incorporate both 3D models' objects and construction activities schedules, sometimes produced by different stakeholders in asynchronous processes. In the BIM approach, the term "level of development" (LOD) is widely used to show that detailing is not only about geometry but also deals with non-graphical information. In 4D models, LOD specification must therefore manage both the graphical level of details and the temporal level of information [8]. In addition, levels of detail must match to business needs corresponding to the expected usage of the model at different stages of the construction project.

This paper presents a multi-phases and multi-LOD 4D case study carried on a construction project in Luxembourg. The theoretical background, the context, the study and its main results are presented. A discussion is finally provided about the findings.

2. Related works and methodology

Case studies using 4D simulation have been reported in literature. In 2002, Dawood et al. used two real life case studies in order to introduce a new approach of extensible 4D simulations development. Their aim was to assess the Man-Hours input necessary to run the model prototype. The two cases studied are a school of health project (a complex project) and a primary school project considered as a simpler project [9]. They concluded that "man-hours increase according to availability of design information".

In 2011, Hartman reported an ethnographic-action research experiment on safe planning of hospital renovations based on 4D models and proposed a method to develop hospital construction process based on 4D simulation [10]. Olde Scholtenhuis and Hartmann presented a second experimentation in 2014 [11]. Using the same ethnographic-action research approach, the researchers explored the influence of scheduling purpose changes on the 4D-model setup. Thus, they studied how practitioners iteratively implemented and used a real-life 4D model. As result, they observed that identifying tasks, allocating resources and communicating among stakeholders are the main purposes at planning stage. Planning logistics, studying dependencies between tasks and mitigating delay are the main focuses of jobsite scheduling. Other recent experiments have been reported including those related to the use of 4D simulation to support workspace conflict analysis [12], path analysis [13], construction quality inspection [14] and fall hazard identification [15].

All these experiments are of course very informative and provide scientific knowledge about development of this technology. But it should be mentioned that only few research focused so far on the particular issue related to the specification of "LOD" for characterizing the content of 4D models. The question of the level of development was only quickly addressed in the 4D research works. In 2000, Koo and Fischer noted that 4D models convey a unique perspective of the project, i.e. related to scheduling, with a dedicated LOD. According to them, it does not enable the various practitioners involved in the project to use the 4D model for other needs. These authors studied the feasibility of 4D simulation in commercial buildings and concluded that users should be able to generate models with different LOD, in order to rapidly explore different alternatives [16]. More recently, Boton *et al.* defined a framework applicable for the design of 4D visualization, in which they mapped the description of a "collaborative situation" to the "informational needs" of a given practitioner (see Fig.3 in [7]). This approach explicitly formulates the content expected in a "4D visualization" for a given context of use, and is applicable when designing visualization techniques (e.g. in software development).

The principle of LOD is to specify the information that the model must contain according to its use at the different stages of a project lifecycle. Numerous definitions were proposed in the context of BIM implementation or BIM guidelines [17–19]. The American Institute of Architects (AIA)'s project BIM protocol is one of the most cited. It defines five levels of development: LOD 100 to LOD 500 [18]. The first level (LOD 100) is limited to a generic representation of the building, used to conduct different kinds of analysis including the cost per square meter, building orientation, etc. The second level (LOD 200) is more precise than the first one but uses generic elements to represent graphically the building with approximate orientation, location, shape size, and quantities. The next level (LOD 300) represents the building with specific elements with additions of non-graphical information. This level can be used to generate construction documents. LOD 400 is more suitable for manufacturers because it exceeds the scope of services of the architect or engineer and provides useful details for manufacture and assembly. LOD 500 model corresponds to the project "as-built" model and incorporates useful elements for operation and facility management. An intermediary level (LOD 350) has been proposed between LOD 300 and LOD 400, to support coordination between different trades during construction [17]. To address the question of the LOD required for particular phases in construction lifecycle, Kriphal and Grilo [20] published a research work about the compatibility between design and construction building information models. According to them, the LOD "grows during the design phase, and reaches its peak during construction". They then stated that level of detail for "design BIM" focuses on geometric complexities, while in "construction BIM" it specifically focuses on the construction resources including equipment, materials, labour and productivity. They also defined the main goals associated with "design BIM" (i.e. visualization, analysis, documentation, coordination verification, quantities extraction and cost analysis) and "construction BIM" (i.e. visualization, documentation, coordination and constructability review, high level of detail quantities extraction, detailed cost analysis, planning and control, procurement, virtual prototyping).

3. Methodology and hypotheses

The research methodology followed in this research is quite similar to the ethnographic-action research approach defined and used in previous research works [21]. In this project, researchers have been trained to 4D software and involved in a real AEC project development, in parallel of the contractual project's team. The aim was not to design new technological development, but rather to analyse the usefulness of market-available 4D technology and to highlight their limits to fit construction management routines in a mid-size construction project in Europe.

Therefore, the initial research hypotheses state that 4D technology can be valuable to construction management practices in mid-size projects in Luxembourg, and have an added-value although 4D/BIM modeling is time consuming. It also considers that 4D modeling is of interest at design stage, especially for early analyses of constructability issues. Finally the research claims that 4D LOD specifications have to fit the targeted project stage, and remain flexible enough to enable both macro and micro usages with 4D models, from global construction sequence to constructability analyses of details. In the following parts, the authors characterize the levels of development of 4D models, across phases of a project, and on the basis of the above-mentioned LOD definitions. Qualitative feedbacks are then provided to discuss applicability and challenges of 4D/BIM implementation.

4. Multi-LOD case study: The NeoBuild Innovation Center

The NeoBuild Innovation Center (NIC) is a building project planned to host the team of NeoBuild, an innovation cluster for sustainable construction in Luxembourg, and other SME companies. The NIC project is highly experimental and the building is designed to support different forms of activities related to construction research, experimental and educational purposes. The project is designed to be a modular, passive and high-tech building. It consists of two floors, with a superstructure made of solid wood.

The construction started in April 2013. BIM has been implemented in the project for multiple purposes: 1) to experimentally model the building, 2) to provide accurate information for the construction site monitoring as well as 3) to include technical data about assets required for further facility management processes. This article focuses on the aspects related to 4D simulation. The experiment presented here was conducted in two parts: the first part at pre-construction phase (advanced design) and the second part during the construction phase.

4.1. Part 1: 4D simulation at pre-construction phase

The first part of the experiment aimed to study the constructability of technical design choices and to anticipate the sequencing issues in early design stage of the project development. The design work was not entirely over at the time of developing the 4D simulation. In particular many technical details remained to be defined but it did not really impact the results of this part of the experiment which was conducted at a "low" LOD. The main actors involved in the simulation were the architect, the structural and energy engineers, the project manager (an actor with technically skills in this project) and the 4D modeler following the information exchange principles defined in Fig.1 (on the basis of the Penn State CIC Research Team's template).

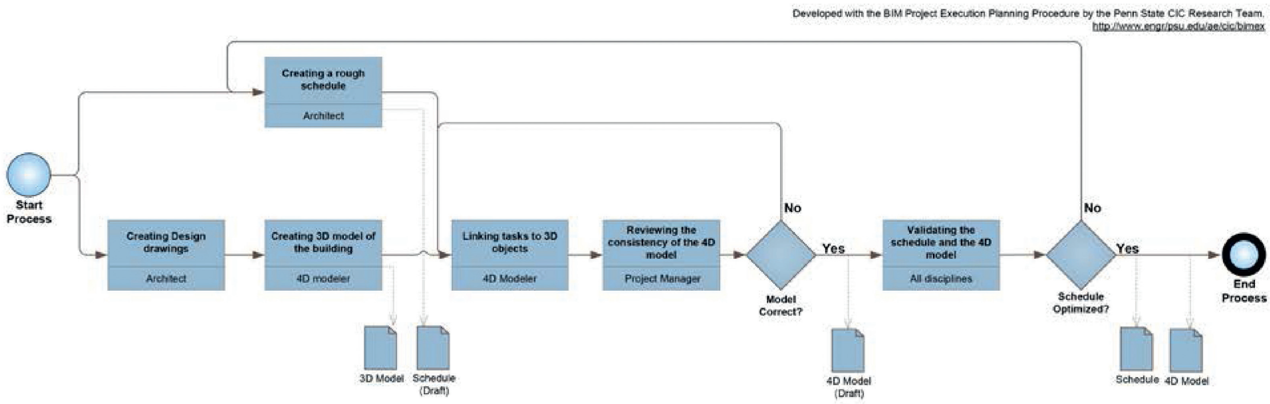

Figure 1: Process Map of the first part of the experiment

Among the goals identified by Kriphal and Grilo [20] regarding the development of "Design BIM", visualization and analysis are the most important ones here. Moreover it should be mentioned that this experiment explicitly addressed the use of 4D/BIM in pre-construction phase for early planning. Therefore it consisted in realizing a first sequencing of the construction activities over time on the basis of a rough schedule produced by the architect, in order to spatially visualize the construction sequences, and to analyse the technical constructability, the possible clashes and the other issues in collaborative team meeting sessions. A particular analysis task studied the front wall construction steps and the interface between the sealing and the glazed wall.

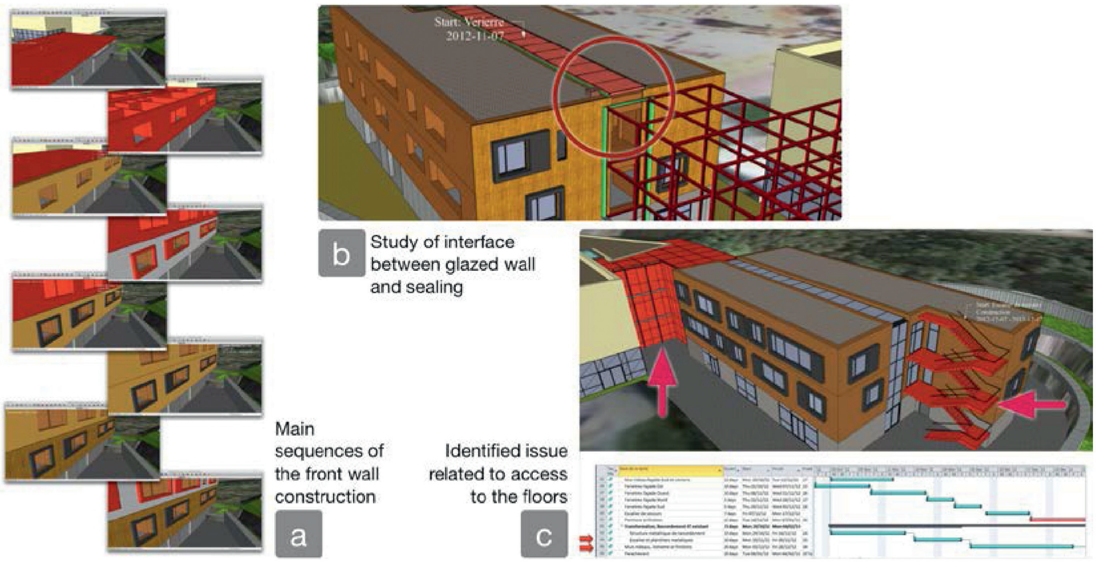

Figure 2: Illustrations from the pre-construction model

The 3D model was created using *SketchUp* at LOD 200 on the basis of architectural design drawings imported from *ArchiCAD*. The volume and the orientation of the building were precisely modelled but many other 3D elements were only approximated. The sequencing of activities was realized directly within the *4D Virtual Builder©* plugin for *SketchUp*. Results and details are directly exported as slideshow in *MS Powerpoint* format. The front wall and the glazed wall were modelled at LOD 300. This enabled the analysis of the wall construction (Figure 2a) and to study with more details the interface between glazed wall and the sealing (Figure 2b, in red). The 4D simulation at this stage made it possible to note that the exterior stairwell and the atrium (Figure 2c, in red) were planned to be built at the same time, after the construction of the main building and the removal of temporary scaffolding. This obviously highlighted an issue for allowing the workers to access to the upper floors of the building, as well as to the roof, because the two main site's accesses were "in work" at same time. The solution consisted in desynchronizing both stairwell and atrium tasks.

4.2. Part 2: 4D simulation at construction phase

The main purpose of the second part, which was developed in parallel with the progress of the building construction, was to control and coordinate the project, to simulate logistics issues and to manage construction site areas, as well as to study more finely some construction details. Apart from the architect, the project manager and 4D modeler, other actors participated in the realization of this part. These actors are the BIM manager, the MEP specialist and the site manager. Many of the goals identified by Kriphal and Grilo [20] appeared in this part of the case study: visualization, analysis, documentation, coordination, planning and control. The aim was to plan, control and coordinate the construction by the various trades, to visualize and analyze conflicts and clashes in models before construction works, to analyze and document logistics management (cranes, scaffolding, restricted areas, etc.). In particular the team aimed also to study in a more detailed way the components of the front wall. The 4D model was built from three information inputs: 3D Architectural Model, MEP Model and a detailed tasks schedule as shown in the Process Map in Figure 3.

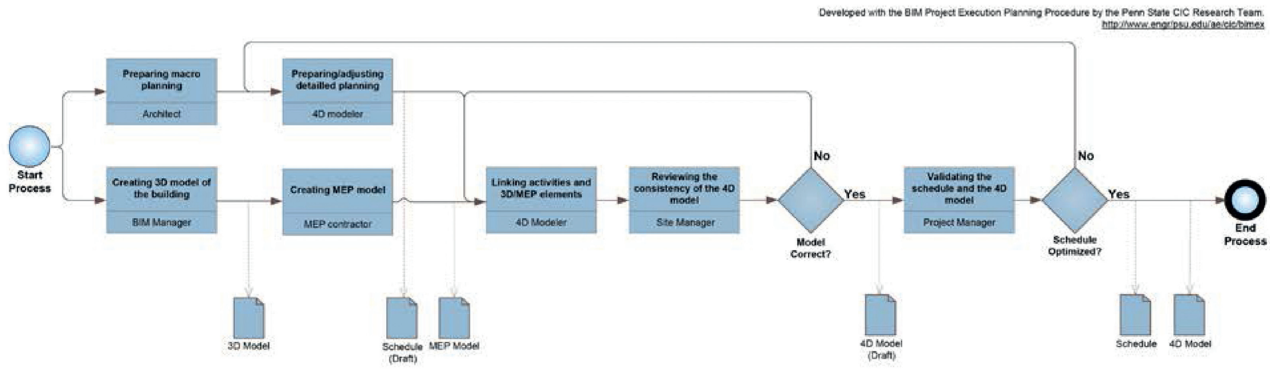

Figure 3: Process Map of the second part of the experiment

Four distinct models were developed. First the architectural model (M1) was created with *Autodesk Revit™*. The level of development of the architectural model was globally at LOD 350, except the front wall that was modeled at LOD 400. At the same time, a MEP model (M2) (LOD 200) was created using *Plancal Nova™* and improved to level 300 (through addition of parameters) with *Revit MEP™*. Moreover, the architectural model was the basis for the creation of a third model with *Revit™*: the logistic model (M3) (LOD 100) with generic logistics elements. The macro schedule proposed by the architect has been detailed in *MS Project™*. All these files have been imported into *Navisworks™* to create the 4D model (M4).

The 4D model allowed the project manager to identify some clashes. For example, some MEP elements were not at the right height level and generated overlaps with the ceiling (Figure 4a). For logistics management purpose, restricted areas, worksite huts and garbage collection areas were indicated (Figure 4b). The positioning of cranes and scaffolding movements were also studied and optimized. The construction of the front wall was studied with accurate details (Figure 4c). The aim here was about the construction sequence of the wooden wall, which is built through many steps involving multiple subcontractors (i.e. woodwork, insulation, and cladding). Moreover windows had to be installed in two separate processes, during and after the assembly of the wall itself. A smooth coordination among actors was then necessary to drill accurate reservations within walls and to ensure that the openings on the wall fit the windows dimensions. This kind of situation often causes issues because of a lack of coordination. In our case, the woodwork subcontractor has been obliged to come back many times to adjust the chambers. The 4D simulation was useful to model the components of the wall, to find the optimal construction sequencing and to provide visual support for contractors.

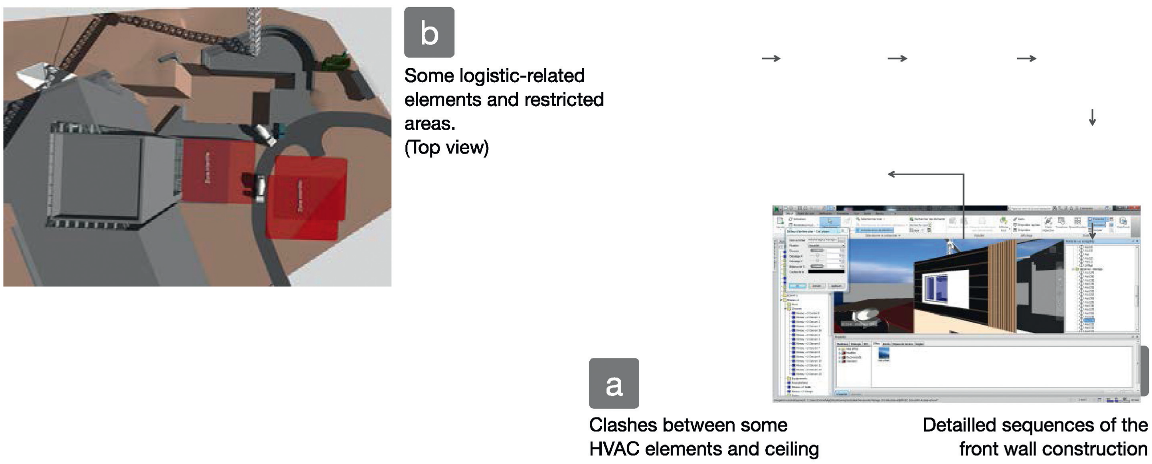

Figure 4: Illustrations from the construction phase model

5. Discussions

5.1. About the work time investment for the case study

In the pre-construction case study, the modeling of architecture components was the most time-consuming effort because data imported from architect's BIM authoring software was not correctly retrieved in *SketchUp* mainly because of errors in the way the software was used. Numerous adjustments were required for correctly linking 3D objects to schedule tasks. The modeling of logistics elements took very less time because logistic model consisted in a few generic logistic elements at LOD 100, mainly retrieved from the *Sketchup 3D Warehouse*.

In the construction phase case study, only the logistics model were created by the 4D modeler. The other models were already created for other purposes in the framework of the BIM workflow approach. It took more time to create the 4D model than in the first part of the case study mainly because the number of elements and details was higher. Although this part aimed to manage more elements and was much more accurate, we noted that it was less time-consuming than the first part. This is because 4D simulation was fully integrated in a wider BIM development workflow where the coordinated architecture, MEP and structure models used had been prepared in previous BIM processes and were reusable by the 4D modeler.

5.2. About the graphical LOD

Overall, the Level of Development was between LOD 200 and LOD 300 at pre-construction phase and between LOD 100 and LOD 400 during the construction phase. Compared to the Kriphal and Grilo work [20], it is confirmed that the level of development required for the construction phase is higher than the level used at pre-construction stage. But the initial assumption that a single LOD is sufficient is not justified, particularly during the construction phase. Indeed, if the analysis and planning have used a unique Level of Development for the two phases, it was not the same for visualization, coordination and documentation for which different Levels of Development were necessary depending on the 4D model purpose and the particular construction issues that arised during the construction and modeling processes. What determines the choice of Levels of Development seems to be the usages and the simulation needs which are not uniform throughout the building development phases and also specific to the project and constructive system.

In addition, the models developed by different stakeholders often present different Levels of Development. Specific issues discovered during the construction process can also require 4D details to be modeled on very limited areas of the project model, either with more or less details (from LOD 100 to LOD 400). Of course, the owner may specify a uniform LOD for coordination goal (i.e. LOD 350 according to the BIM Forum working group). But, as observed in our cases some simulation needs may require to model with more or less details a few elements without this required Level of Development being necessary for the entire model.

5.3. About the temporal LOD

Managing the correspondence between the graphical LOD and the temporal LOD is not a trivial issue in 4D simulation. In the first part of the experiment (pre-construction phase) only a rough schedule was available. Approximated sequences of construction process were proposed by the 4D modeler mainly based on the major changes from one step to another and not on dates nor milestones or work breakdown structure. The temporal LOD was therefore derived from the 3D model LOD. But a detailed planning was made available from the beginning of the second part of the case study (construction phase). It was a macro planning with a very low LOD, showing the major stages of the construction process. The Project Breakdown Structure elements were not at the same LOD as the 3D models elements. In addition, the site manager had a more detailed schedule but it did not cover the whole construction process. It was therefore necessary to the 4D modeler to define an additional work sequence representing detailed activities in order to make them correspond to 3D models elements.

The creation of this detailed planning has led to a considerable workload. To the extent of our knowledge, this is mainly due to the lack of guidelines for managing temporal LOD requirements. Indeed, it was necessary to export a selection sets nomenclature from 3D model, to sequence the activities corresponding to these selection sets, and to validate the sequences with the site and project managers. It was then also necessary to import the new schedule in order to link construction activities to 3D building elements. This suggests that it might be interesting to define standardized temporal LODs, which correspond to the graphical LODs of BIM approach. The ultimate goal can be the creation of standardized 4D LOD, as combinations of graphical LOD and temporal LOD. The seminal research performed by Aalami et al. [22] can be a very interesting starting point.

5.4. About the bidirectional exchange between the construction site and the model

The second part of the experiment took place during the construction phase. It was a situation of interesting bidirectional communication and exchange between the 4D model and the construction site. It was then possible to study thanks to the model a number of problems and to anticipate them before they appear on the construction site. But the model also benefited from feedbacks from the site. Indeed, some problems appeared on the construction site before being studied on the model. In such cases, the feedbacks from the site made it possible to run simulations on the 4D model in order to analyse alternatives, to choose the best solutions to apply on site, and to update the model. For example, it was the case of the front wall construction (see Fig. 2).

Some problems on the site could not be solved with the 4D simulation because of the limitations of the software features. For example, the site manager wanted to automatically generate cable-trays according to the position of cranes and space constraints of the site. The aim was to ensure that electric power supplying was still possible especially when mobile cranes were at some particular locations. This feature was not covered by the software used. A solution of non-automatic cable-trays has been used.

6. Conclusion

This paper reported a 4D simulation case study conducted on the NeoBuild Innovation Center project in Luxembourg. The first part of the experiment was conducted at the pre-construction phase and aimed at studying the constructability of technical choices as well as at anticipating sequencing issues in collaborative team meetings. The second part was conducted during the construction phase and the aim was to coordinate the site work, to simulate the logistics and site areas but also to analysis more precisely some construction details.

It was shown that it is required to manage multiple graphical LOD corresponding to the different usages of the model either expected (i.e. required) or unexpected (ad-hoc analysis with the model). Moreover different parts of the model came from different actors with different LOD. The graphical LOD necessary for construction phase is higher than the graphical LOD at pre-construction phase. Uniformed temporal LOD should be proposed and validated in order to define LOD for 4D/BIM purposes, a first step towards models sharing among 4D tools. The bidirectional exchange between the construction site and the 4D model in the second part of the experiment was another very interesting finding. In future works, authors will work on the issue of 4D LOD specifications, including temporal LOD description and correspondence between temporal LOD and existing graphical LOD in BIM approaches.

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