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4D modeling and simulation for the teaching of structural principles and construction techniques.

Towards modeling and visualization guidelines for high-rise buildings.

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Abstract. 4D CAD is more and more used in construction education curricula. The main interest of this technology is its ability to simulate real sequencing of construction tasks in order to confront the student with real-life construction management issues. This article presents a course for architects and construction engineers. It describes the teaching of the structural principles of high-rise buildings, using 4D simulations as a support to the analysis of the characteristics of existing projects. The pedagogical interest of 4D CAD is described in the article through assessments of students and the teaching team. Particular feedback is given about modeling and visualization guidelines for the purpose of the pedagogical use of 4D CAD.

Keywords. 4D CAD; 4D modeling and visualization; High-Rise Building; Structural Principles; Pedagogy.

1. Introduction

The University of Liège in Belgium offers curriculums for the initial training of engineer-architects and construction engineers. Specific Master courses are developed for the teaching of organizational issues in large construction projects and the management of teams in charge of complex projects. Some issues could be noticed regarding particular types of construction projects or management techniques:

- The design principles of high-rise construction projects are not really tackled in the current curriculum. Moreover, the necessary *multi-expertise* of project management methods during the design and construction phases is not part of usual architects/engineers trainings.
- When it comes to the teaching of planning methods, traditional planning courses sometimes appear to students as disconnected from reality. Indeed, they are not really aware of the “in-situ” conditions of construction projects.

From these statements we proposed an original pedagogical scenario inspired by the recent advances related to 4D technologies in the Construction IT research community (Hartmann et al. 2008) and their application in pedagogy, e.g. (Russell et al. 2005; Sampaio et al. 2006).

2. Pedagogical approach to 4D modeling and simulation.

One can recognize that it is usually difficult to address 1) the issue of high-rise design, 2) the technical aspects of tall buildings structures and 3) the characteristics of high-rise construction processes, within a single and short-duration course. Then, 4D CAD appears as an interesting technology to help students better analyze the design and construction of high-rise buildings, and especially their structural principles.

2.1. State of the Art.

Construction projects management courses are very diversified in architecture, engineering or construction curricula (Dietz et al. 1976). In architecture curriculums, it is usually stated that architecture students do not gain much practical knowledge of construction management and methods (Clayton 2002). With the emergence of computer-supported 3D building modeling, innovative methods are being more and more explored in order to improve the construction education experience. (Clayton 2002) described a virtual construction exercise experience with students using 3D CAD and simulations. He concluded that virtual construction is very interesting to teach construction management to students more easily through many learning situations or projects examples. (Perdomo et al. 2005) presented a study in collaboration with the Virginia Tech architecture and building construction department that was investigating the educational advantage of 3D representations over 2D drawings in terms of understanding construction assemblies and details. The results were very positive.

But, in curricula addressing complex “construction environments”, like bridges, towers or the construction of high-rise buildings, it is important to address technical issues while taking into account the various topics to be included in short-term courses. Indeed, such projects require treating a vast scale of parameters, working at multiple levels of detail, dealing with design variability, and realistic representation of the work (Russell et al. 2009). Students have to understand the difficulties related to the steering of such projects, as well as the nature of design decisions that have to be taken. Therefore, it is important to include the temporal dimension related to the scheduling, in order to explore and analyze the constructability of working methods. 4D simulations appear to be an innovative solution and some teachers already have implemented them in their courses. (Kang et al. 2004) presented a web-based interactive 4D block tower model for construction planning and scheduling education and showed 4D visualization interests for education. (Sampaio et al. 2006) demonstrated through many examples that virtual reality, including 4D CAD, can be useful in teaching material elaboration. (Wang et al. 2007) described a study to assess the value of using 4D modeling in construction engineering courses and compared results from two different 4D processes that are traditional 4D and virtual construction simulators. Both processes were found valuable to improve the learning experience of students.

Moreover, the usefulness of 4D models to support collaboration in the construction industry has been demonstrated in some research works. Indeed, using 4D simulations can increase collaborative scheduling (Mahalingam et al. 2010; Zhou et al. 2009), site coordination (Dawood & Sikka 2007) and communication (Heesom & Mahdjoubi 2004).

2.2. Course description.

The pedagogical scenario retained for the course consists in both theoretical courses and practical works. Practical works are themselves divided into two stages: single-student work and teamwork.

- Theoretical courses aim at providing students a basic knowledge in the fields of high-rise buildings and project management. Structural constraints and common solutions are the main topics of the courses. A typology of construction principles is presented. Vertical transportation systems, as well as façade techniques, are also dealt with. The second part of the course introduces project management, especially in terms of organizations of actors, coordination mechanisms and finally IT-supported collaboration. BIM and 4D modeling/simulation is the final theoretical input.
- Practical works consist in analyzing high-rise building projects. In a first stage (4-5 working weeks), each student is expected to analyze various aspects of a project. Then in a second stage, students are grouped in teams of 3 to 4 students. Each team chooses an existing building and has to realize a complete analysis of the structural principle and construction process. Then, they have to propose a 4D simulation “scenario” which aims to provide a “didactic understanding” of building structures and construction. 4D modeling and simulation themselves are the final part of the teamwork.

3. Feedback on the course.

This course has been taught three times, during the fall semesters of the following academic years: 2009-2010, 2010-2011 and 2011-2012. 14 students were involved in 2010, 12 students participated in 2011 and they were 15 in 2012. In 2010, 3 teams worked on New-York Times Building (New-York), Sears Tower (Chicago) and Debis Tower (Berlin). In 2011, 4 teams worked on Caja Madrid, Opernturn (Frankfurt), Shard London Tower and the World Financial Center (Shanghai) towers. And in 2012, 6 teams analyzed Puerta del Europa (Madrid), Bligh Tower (Sydney), John Hancock (Chicago), Tower 0-14 (Dubai), Triangle Tower (Köln) and Heron Tower (London).

3D modeling is realized with *Google SketchUp™*, and 4D modeling and simulation is enabled thanks to the courtesy of the D-Studio company, providing its *4D Virtual Builder© for Google SketchUp™* plug-in.

3.1. Teaching team's feedback.

The course presented above is experimental in the engineer-architect and construction-engineer curriculums of the University of Liège. It was designed in the continuity of the previous course of project management, which was dedicated to the understanding of particular constraints related to the planning and design of large-scale projects. The main hypothesis is to benefit from 4D modeling and simulation technologies. The feedback of the teaching team is the following:

- Firstly, the use of 3D modeling tools like *Google SketchUp™* is possible and valuable, also when students are not familiar with 3D modeling (it is the case of the construction-engineers students). *SketchUp™* is rapidly understood and usable by all of the students.

- 4D modeling of high-rise buildings (although the aim is not to provide a very fine-grained planning) requires a deep understanding of structural principles, because it impacts the skeleton of the construction planning (i.e. the Work Breakdown Structure). The *pedagogical team can better appreciate the completeness of students' analyses*. This is due to the need of clearness when modeling the buildings' main structural 3D elements as well as the schedule's WBS.
- Finally, as documentation on high-rise construction is usually difficult to obtain (planning as-realized, detailed plans, etc.), students have to infer both structural principles and construction planning. It requires that they make hypotheses on the design and that they find evidence of construction procedures (photos, webcam, or TV documentary). The *exercise then becomes original* compared to classical "planning" or "structure" courses and students get more easily involved and motivated.

3.2. Students' feedback.

The feedback of students is related to their use and appropriation of 3D/4D technologies and is supported by the results of a survey carried out on 2012 students.

Students appear to be very interested in the opportunity offered by 4D technologies for the simulation of construction projects. They particularly understand the interest of construction planning analyses supported by 3D visualization. Compared to other courses, 4D models help them to better understand what really lies behind the planning of a task. They also appreciate learning about high-rise design and construction, which is not a usual topic in their curriculums.

However, we underline the limits of their understanding of the utility of 4D modeling in professional practice. The structured surveys described in the next section highlight this issue.

4. Challenges for the pedagogical use of 4D-CAD.

4.1. Survey carried out at the end of the 2011 course session.

In the last session (2011), we decided to carry out a survey analysis in order to evaluate the students' feedback on the use of 4D tools, as well as to assess their understanding of the utility of 4D CAD in the professional life. Indeed, this particular exercise helps students understand the principle of 4D CAD, and lets them experience it on the analysis of structural principle and construction process of a single project. Therefore, the application is quite different than most of the usages of 4D CAD in real construction projects, for constructability analysis in the design phase or construction progress monitoring in the construction stage.

The first part of the survey consisted in an evaluation of the satisfaction of users, based on the SUS scale (Brooke 1996). Although the SUS score is quite low (39,82/100), the principal aim of the survey is then to finely assess how students understand the utility and applicability of this technology for their future professional activity. A more detailed questionnaire is based on a set of questions targeting the assessment of utility and usability of 4D CAD.

4.2. Results.

Table 1 summarizes the results obtained through the survey. 14 students answered the questionnaire. The analysis of the students' feedback demonstrates that they have difficulty imagining that the 4D simulation can contribute to improve their future professional work, to make it easier and globally allow them to gain time (see part "productivity" on Figure 1). We think that we can mainly explain this nature of feedback (fundamentally different from professionals that make use of 4D simulation) by the fact that they have a partial view of the mission that will be theirs in the professional environment. Moreover, during this experiment the students have to manipulate three tools: 1) Microsoft Project for the scheduling of the construction tasks, 2) SketchUp to model the building, and 3) xD Virtual Builder for 4D simulations. At the beginning of the course, they have already studied Microsoft Project but have no experience in modelling softwares. Therefore, they have to assimilate SketchUp as well as xD Virtual Builder. The exercise appears complex for the students who are less skilled with this type of software. Consequently, their vision about the time required for the 4D modelling is relatively biased. We can consider that it is one of the limits of the proposed pedagogical device.

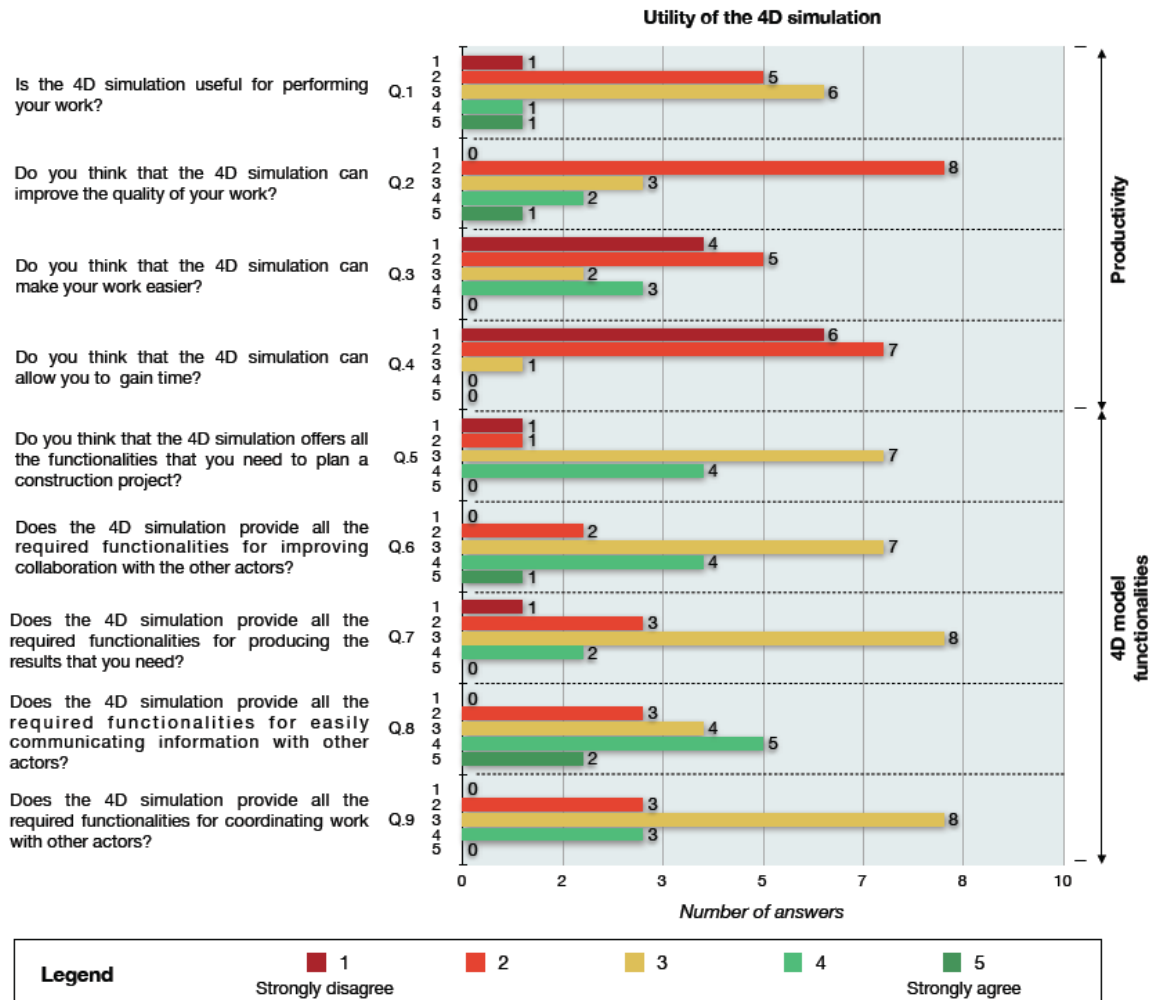


Figure 1: Survey results.

About the 4D model functionalities, the students' feedback is more positive (see part "4D model functionalities" on Figure 1). It appears they feel that 4D simulation contributes to the communication between actors and improves collaboration.

Beyond introducing 4D simulation, this feedback from the students justifies our aim to improve visualization in the applications of 4D-CAD. Moreover, as students do not really have to convince clients, we consider that the role of visualization in the particular case of our exercise is to communicate the analysis of high-rise structural principles. Then, each group of students has to develop its own "visualization framework" to carry out the messages of their structural analyses.

5. 4D modeling and visualization for high-rise buildings: some statements.

Communication and collaboration-support are well-known benefits of using 4D-CAD in construction projects. As demonstrated by the survey results, described in the previous section, it is essential to sensitize the students to the visualization while they are using 4D modeling software tools. Moreover, visualization choices can help them in expressing their theoretical analysis of a building project. The research that we develop in the field of 4D visualization leads us to propose a matrix for the analysis of visualization and some results about particular 4D visualization for high-rise buildings.

5.1. Modeling of the construction of high-rise buildings.

The projects of four students' groups were analyzed in a previous paper (Kubicki et al. 2011), both in terms of modeling and visualization. Concerning the modeling, our analyses showed that:

- The *modeling of architectural projects is generally simplified* for the aim of simulating the construction process. Indeed, with the aim of establishing the links between 3D objects and schedule's entities, the level of detail is usually lower than for architectural modeling and visualization (rendering),
- The principal variables in modeling, in the case of high-rise buildings, are the *type of floor*, standard or non-standard, as well as the *elements shown* in the model, and highly dependent of the *construction material* (steel, mixed steel-concrete or armed concrete).

5.2. 4D visualization of the construction of high-rise buildings.

The concept of multi-visualization is generally used for visualizations where data are represented by using multiple windows. Such views can be independent and isolated, or tightly coordinated. Coordinated multiple views (CMV) describe two or more distinct views tightly coordinated and used to support the investigation of a single conceptual entity (Roberts 2007). In construction, 4D simulations can be considered as CMV systems since they suit these rules. Indeed, 4D visualization usually makes use of different views (i.e. 3D view and temporal view) and data sets displayed in the views are logically linked.

In a parallel research effort (Boton et al. 2011), we developed a classification of attributes of 4D visualization enabling to describe both the content, structure or graphical characteristics of the 4D views and the coordination mechanisms that logically link the various sub-views.

In the students' works, one can distinguish the characteristics related to the visualization properties of the 4D model, and the final presentation of the 4D simulation. The visualization properties of the 4D models are:

- The *semantic of colors*. Usually 4D-CAD software tools propose standard sets of colors to visualize 4D models: red=task in progress, transparent=task not started, etc. In this course, we encourage the students to give significance to the colors they used. Beyond the state of tasks, the students use colors sets to distinguish the *structural status of 3D objects*, i.e. variations of colors depending on the load-bearing role of objects, transparency for non-structural objects (e.g. facades) enabling to visualize the primary structure inside the building, etc.
- The *representation of schedule* information. Schedule is an important component of 4D models. It is usually mentioned as a date, milestone, or step in the planning of tasks. Then, the representation of time can take various forms in the models of students, but it usually is a simple display of the ongoing date, highlighted above the 3D model. In some cases, a dedicated Gantt View is used. But it should be mentioned that the exact date is not capital information in the framework of our 4D models. Indeed, the *sequence of construction tasks* is more important to understand the construction process, and can be represented with colors associated to the 3D objects.
- The *camera principles*. The visualization of large-scale buildings is a remaining question in the CAAD community. Moreover, in the case of construction simulations, tasks can happen at a given date, in many locations. Then the use of camera principles is different in each particular case. We can notice the following approaches. *Zoom* is used to show a particular object or group of objects, and can present particular works in a given space. *Extended zoom* shows the entire building and can be used to give an overview of the construction principle (e.g. core/primary structure/secondary structure/facades). *Sections* or *interior perspectives* were also used by the students, e.g. to show construction details inside the building. Finally *orbit* enables the widest view on the building construction progress.

5.3. 4D multi-visualization of high-rise buildings construction.

The SketchUp plug-in that was used allows to define colors/transparency properties of the 4D objects, directly in SketchUp. It also allows the user to export the 4D simulation in the form of a Powerpoint presentation, enabling to personalize the multi-visualization layout. Two interesting layouts are described below.

In the first example, the aim is to represent parallel tasks that are performed in different areas of the 3D models. While analyzing the construction of the “0-14 Tower” (in Dubai), the students were confronted to the parallel sequencing of “facade construction” (double skin concrete façade, with holes) and a “podium construction” which is connected to the main building. The use of a two-window multi-view representation (Figure 2Figure 1) enables, for each date, to focus on both global construction of the skin (left part) and the detailed steps of the podium edification and its connection to the skin (right part).

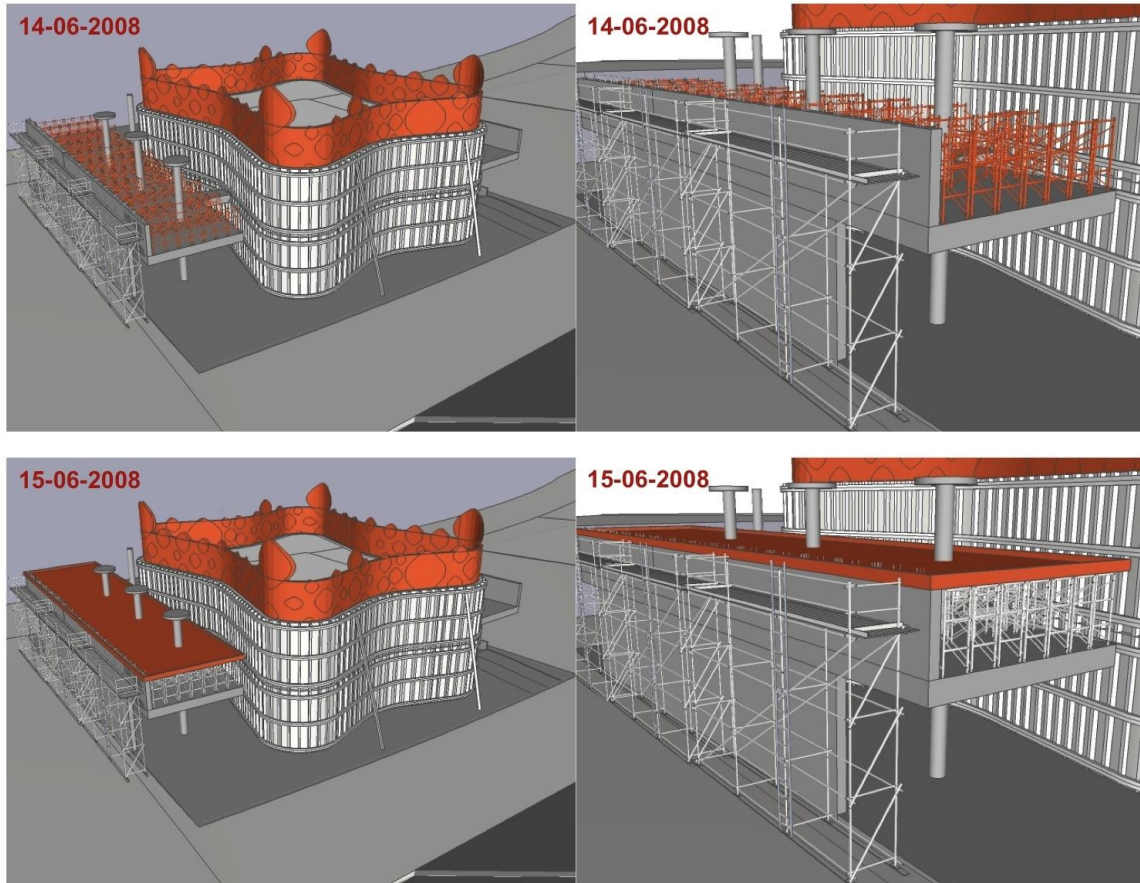


Figure 2: 4D multivisualization composed of two coordinated views for each date.

In the second example, the Heron Tower (in London) has been analyzed. The main findings of the students' analysis showed that the particularity of this building was the multiple structural systems of the façades. Indeed there are three types of façade systems in this project: 1) “small windows” façade, 2) glass wall façade, and 3) bracing system over glass wall. Moreover, their work addressed the question of visualizing multiple areas of a large-scale construction project (i.e. high-rise). As same-time scheduled tasks can be executed in distant locations, there is a real issue for the visualization of these locations.

The proposed multi-visualization firstly distinguishes the areas represented in the simulation: for a single date, the students proposed to visualize two sides of the building (two representative façades) as well as one extended view and two detailed views. Moreover, they divided the vertical representation of the façades using four camera principles (four different zoom settings) to better represent the targeted areas. [Figure 3](#) illustrates this 12-view representation (note that the 12th view was not active at the date displayed) for a single date.

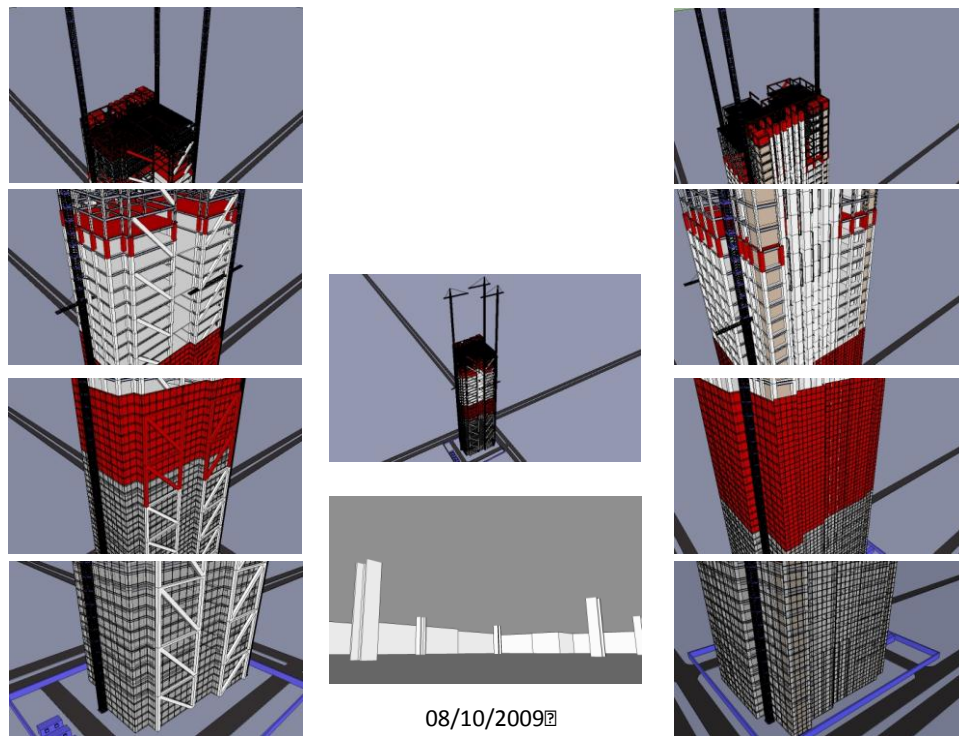


Figure 3: Multi-visualization of the construction sequence of the Heron Tower (London)

6. Conclusion.

The article describes a course dedicated to project management in construction. The particular subjects of teaching are the structural principles and construction processes related to high-rise buildings. 4D CAD assists the work of students, who have to analyze a particular existing building during the session.

The article highlights the feedback of both teaching team and students, based on a survey carried out at the end of the course. The main result is that 4D CAD seems to be useful to the work of students but that it remains difficult for them to understand its added value in real professional life. An important challenge is the visualization of the 4D simulations. A relationship is then established with research work about the design of multi-visualization interfaces. Some conclusions are provided on the basis of simulations involving two students, and they allow to envisage prospects towards the elaboration of guidelines for 4D CAD visualization, which could be useful for other curriculums.

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