BUILDING DESIGN COORDINATION: COMPARING 2D AND 3D METHODS

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Coordination of Mechanical, Electrical and Plumbing (MEP) systems among themselves and with the architectural, structural and other building systems is an important, challenging and time consuming task on the design phase of multistory buildings. Many researchers have already expressed a critical view on the most widely adopted coordination process, which makes use of transparent trade drawings overlapped on a light table for detecting conflicts. The use of a 2D CAD system is nothing but a direct replacement for paper drawings and light table, not considerably changing the method. The authors of this paper, like others, advocate the use of 3D CAD for the coordination process as a more apt tool for this spatial task. Two studies were conducted to compare the performance of a 2D CAD-based coordination method to that of a 3D CAD supported process, both in terms of efficiency and efficacy. Both methods used 2D CAD drawings as input but the three dimensional process required subsequent solid modeling of all relevant building systems. Even with this additional burden, the 3D-based method outperformed the traditional one. Results show its higher efficiency as there was a significant decrease in the time spent for detecting interferences during the development of a masonry production design in an experimental study. The higher number of conflicts revealed in the plumbing design for a multistory building demonstrated also its increased efficacy in a case study.

KEYWORDS

design coordination, 2D CAD, 3D CAD, efficiency, efficacy.

1. INTRODUCTION

Design coordination of mechanical, electrical and plumbing (MEP) systems is a challenging process on complex building projects (Korman and Tatum, 2001). It may be defined as the arrangement of components of building systems into the structural and architectural envelope of the edifice and today it includes not only mechanical (HVAC and elevators), electrical and plumbing systems, but also fire protection, automation and control, CCTV, electronic security systems, video, voice and data systems, among others.

Although today not all contractors invest enough in the coordination process (Riley el al., 2005), it is considered an essential link to the successful design and construction of these systems (Korman and Tatum, 2006). Research (Riley and Horman, 2001) has indicated that investments in coordination reduce conflicts and change order costs generated on the field, paying for their cost, and producing many more benefits (less disruption of productive workflow of different trades in the field, fewer conflicts and interruptions to crews, more reliable work environments, etc.), specially in MEP intensive projects.

While Korman and others (2001, 2006) use the term “coordination” meaning only the activities regarding the (soft and hard) interferences among building systems (focus on apparatus), we prefer to call those actions “compatibility/interference analysis”, giving the term “coordination” a more global sense, which includes the first meaning, but also regards the management and harmonization of the activities of all specialty contractors among themselves as well as with other project stakeholders (focus on agents). Despite that, in this work it will stick to the expression “MEP/spatial coordination” to identify the interference analysis among building systems.

In Brazil, it is often contracted a detailed masonry wall design as part of whole systems design. The masonry designer aims to optimize the material and labor use for constructing each masonry wall, while making sure its design is correct from an engineering point of view, i.e., regarding stability, performance, durability, constructability, etc. This design is especially important in Brazil, because national structure standards permit slim concrete structures which have a considerable deformation upon walls. Also, a complete interference analysis on the building systems and other components that are constructed inside the walls (piping, electrical ducts, structure, windows, doors, etc.) is required to reach the masonry designer goals, as optimal brick/block positioning depends on it. Soon this interference analysis turned into one of the outcomes contractors expect from them, sometimes rendered as an even more important result than the masonry design itself.

In their research in the U.S., Korman and Tatum (2001, 2006) identified the SCOP (Sequential Comparison Overlay Process) as one widely adopted MEP coordination process. In SCOP, interference checking is accomplished by plotting shop drawings from all concerned trades in translucent media (e.g., tracing paper), on the same scale, and overlaying them over a light table. Although lacking a formal study, one could say that in Brazil (Schmitt, 1999) and probably in most countries, that same overlay method is used as a primary tool for coordination, either on print media or, now more commonly, electronically with 2D CAD.

The MEP coordination process has been performed with a great deal of different technologies, from paper-based SCOP to 3D CAD, depending on the size and technological maturation of the contractor.

The introduction of 2D-CAD was an improvement over the paper-based method, as layers can be easily turned on and off, simulating a speedy overlay of tracing paper sheets over the light table. Also, expensive plotting for this process was no longer necessary, as analyses can be conducted over the computer display. Despite these advances, the 2D CAD-based process does not change considerably the paper-based method as all the drawbacks of a complete manual analysis are still present, requiring a recurrent mental effort for reconstructing tridimensional entities from a 2D representation.

On the hi-tech end of the spectrum today are tools based on object-oriented, parametric 3D models. Tatum and Korman (2000) pointed out, some years ago, that capturing the knowledge of diverse trades and integrating them on software customized for the needs of MEP coordination was a major challenge in this field. The recent development of BIM (Building Information Modeling) software may now be providing a more straightforward landscape for such undertaking.

An intermediate process between 2D-CAD and object-oriented/parametric 3D-CAD is standard solid modeling. This technique allows performing hard interference checking (Neggers and Mulert, 1993) as long as all components from relevant trades are modeled.

Riley and Horman (2001) have stated the promise and suitability of 3D/4D CAD for coordination in the future, but mentioned building contractors perceived it to be too costly for widespread use, at that time.

Korman and Tatum (2006) advocated a revised process for integrating a knowledge-based tool in the MEP coordination practice: a 3D CAD file would be generated and forwarded to a central location by each specialty contractor. Those files would then be integrated and analyzed by a MEP coordination tool, which checks and corrects the detected interferences.

Since 1992, one of the authors of this work has used 3D CAD for interference checking while developing detailed masonry designs (also in 3D). This activity was performed within a traditional setting, where all the other project agents (architect, specialty contractors, and structural engineer) worked with 2D drawings both as input and output for their tasks. Therefore, a complete 3D model had to be produced from 2D-CAD files and the final design had to be represented as plan and section views for delivery. The business success of this approach led us to believe that, although the solid modeling of all building systems was a significant burden, the total time of this 3D-aided process was reduced compared to the 2D-CAD overlaying method and its efficacy was, at least, the same.

The aim of the work presented in this paper was to compare the performance of a 2D CAD-based coordination method to that of a 3D-CAD-supported process, both in terms of efficiency and efficacy.

2. SPATIAL COORDINATION METHODS

The following sections summarize the main characteristics of the two methods compared in this study.

2.1 TWO DIMENSIONAL CAD COORDINATION METHOD

Manual or paper-based and 2D CAD coordination methods have essentially the same framework, as stated before. These methods are based on the use of bidimensional graphics representations (floor plans, sections and views) as a tool to analyze and, at the same time, represent the designed solution. A lot of design time is spent on inferences about the real 3D space. The spatial information is registered into the designer and other stakeholders' minds demanding abstraction and good operational memory from them.

Ferreira and Santos (2004) have shown that traditional 2D design (including 2D CAD) implies recurrent interpretation of graphic representation, mental analysis, codification of graphic solution (into an abstract and often partial format), followed by checking and correcting activities. This cycle demands from the designers experience, spatial abilities and acquaintance with the technical representation. Even seasoned professionals may make mistakes in complex situations, in projects with many or dense building systems and/or unconventional designs. Within this method, design processes and solution documentation take place at the same time. Little design automation is possible with this method. Even drafting aid is small, compared to the fully automated drawing of plan and section views enabled by 3D CAD.

2.2 THREE DIMENSIONAL CAD COORDINATION METHOD

With the 3D-based method, designers and other technical stakeholders analyze the objects in space through solid models. Interference detection can be done visually or automatically using the intersection boolean operation.

The solid modeling process itself allows the designer to promptly detect clashing components and design inconsistencies. Those problems are immediately corrected or marked to be the forwarded to the appropriate professional. Furthermore, because the representation is not as symbolic and abstract as that of the 2D process, the demands on the designer regarding training, spatial visualization ability and knowledge of technical drawing are much lower. As a consequence, it is expected fewer mistakes to be made and more design problems to be early detected than with 2D-based methods.

In this method, the final design documentation produced is similar to the 2D CAD output, although their generation processes are quite different. When using 3D CAD, the software creates floor plans, sections and views automatically from the solid model, usually at the end of the design process. Dimensions, notes and sheet layout are done manually, eventually with some small automation routines, like in the 2D CAD method.

In both the studies in this report, the 3D CAD package was augmented with some LISP routines to increase efficiency of repetitive activities, as well as of sequences of commands frequently used.

3. RESEARCH METHODS

Two research strategies were adopted in this investigation. Firstly, a controlled experiment was set up to compare the efficiency of the 3D-CAD method to that of the 2D-CAD coordination process. Then, a case study was conducted to investigate their efficacy, regarding detection of interferences and constructability problems.

The first experiment was conducted in the first semester of 2004. The case study was observed during 2007.

Both phases in this research involved the production of detailed masonry designs as, in Brazil, this is the activity supposed to detect most of interferences among building systems, structure and masonry itself.

3.1 EFFICIENCY STUDY

For comparing the efficiency of 2D and 3D methods, an experiment using a real case was structured. An arrangement was made with a traditional masonry design office (Office A), which agreed to participate in this study as well as one of its clients. A project from this client (a major contractor) was selected for close monitoring. All the activities of the design office members related to this project were registered in a time sheet. Designer name, date, start time, end time, task name and a short activity description were recorded whenever some task related to the target project was performed. The team members were instructed to register their doings each time they started, interrupted or finished an activity on the selected project.

Three professionals from Office A worked directly in this project: one design coordinator and two trainees. The coordinator was a 22-year-old engineering student, graduated as a building technician four years ago. He took this position two years before, after working for two years as a trainee in the company. He reports directly to a manager who supervises the design work. The trainees were 18 and 19 years old and were graduated 12 months ago from medium level courses. The coordinator works, on average, on three different projects at a time, while trainees work on a single one.

The design process at Office A is the one described in section 2.1. The tool used was AutoCAD R14. The company had been designing masonry for seven years.

About the same time, using funds from a research grant for this study, another masonry design office (Office B) was hired to develop exactly the same project. This second office belongs to one of the authors of this paper and had more than a decade of experience in producing detailed masonry design using 3D tools. This office does not have permanent employees and temporarily hires designers who were previously trained in its premises for working with 3D CAD, on a demand basis. Starting as trainees in this office, these professionals learned not only to model in 3D, but also the particular internal processes (Ferreira, 2007) developed to enable efficient design work coordination as well as to use the custom CAD routines created to automate some of the recurring tasks of masonry design.

This office used the process described in section 2.2 and adopted AutoCAD R14 and AutoCAD 2000 as primary tools, along with some custom AutoLisp routines.

For this study, only one designer was involved with the project, assigned exclusively to this task. She was a 26-year-old architect, graduated about two years before, who worked previously as an apprentice in this office for 30 months.

The same time-recording procedure was adopted in this case. No document or information was exchanged between the two offices. Their members did not have any kind of contact during this study and the designers had never met before. To avoid any information leak, the author who owns Office B and who normally acts as a design manager, did not work in this project, which proceeded without management interaction with the designer. This was not critical, as this job was hired only for this study. Because of that, and also because time spent on management activities, including team meetings, are difficult to compare fairly, it was not computed in any of the offices. Also, the time spent in modification tasks resulting from decisions made by management was also excluded.

The designer in Office B received the same documents Office A was provided by the contractor, i.e., architectural, structural and building systems designs in 2D CAD format. Change orders from the client to Office A were also forwarded to Office B.

The construction project used for this experiment was a twenty-story multi-family apartment building with 6 units per floor. Only two basic apartment floor plans were designed as 4 units were mirrored versions of one layout and two units were rotated versions of another one. The total number of distinct walls in the typical floor plan was 69 from a total of 148.

3.2 EFFICACY STUDY

Although the project used in the experiment for the efficiency study could also, at first, be used for efficacy comparison, data analysis showed no significant differences in the number of interferences detected by both methods applied to that project. The reason for this is probably due to the fact that the architectural and building systems design solutions adopted in that project are very well known to all designers in offices A and B as it was repeated with minor modifications, in several projects they worked on before. Kim and Wollemon (2003) have studied the sources of complexities on the new product development environment. One of them is the technological newness. One could characterize the complexity of the first project as very low, because it was not new at all, dismissing any special help the better visualization provided by the 3D methods could provide to the designer. Therefore, a more complex project was selected to comparatively evaluate the efficacy of the 2D and 3D methods.

A case study strategy was used for comparing the efficacy of 2D- and 3D-based methods. A more complex project from a major Brazilian building contractor, which included masonry detailed design, plumbing assembly kit design and façade detailed design, was observed. These three subsystems were analyzed using the 3D-CAD method described in section 2.2 for coordination purposes.

The Office B (the same from the previous experiment) developed those designs using AutoCAD 2005 and 2007, with AutoLisp routines, modeling the subsystems components as 3D solids.

The residential building of this case study has 29 apartment floors, 3 basement floors for garage, a common area at the street level with gardens, swimming pools and other leisure equipments. There are also 3 upper floors used to shelter a water tank and the elevator equipment. The project area totals 17,400 m2 for the building construction in a 2,500 m2 urban lot.

During design, the specialist registered the detected interferences, so that they could be solved later by the other systems specialists and the design coordinator.

4. ANALYSES

4.1 EFFICIENCY STUDY ANALYSIS

More than 200 records were registered in the time sheets by both design teams.

Trainees' activities accounted for 72% of the total development time at Office A. The coordinator was responsible mainly for checking and finishing activities, including correction of mistakes. In Office B, of course, the only designer performed 100% of all activities.

A number of activities were identified from the data collected. These were grouped under generic denominations, as shown on Table 1, due to the difficulty for discriminating the time used in each process of a single activity. For example, the generic activity "2D Design" includes both the time it took the designer to analyze a problem as well as that for drawing its solution. In the same way, "3D Design" encompasses the time for modeling, analyzing, checking, and correcting the design, because all these activities are done iteratively, in a continuous flow of operations, which could not be registered independently by the designers.

Some activity names were reported in both the 2D and the 3D methods, although in practice they reflect very different procedures. The times for every individual activity of each generic group were added up. Totals for each activity group as well as for the whole design work for both methods were obtained and compared.

Table 1: Description of Generic Design Activities

GENERIC ACTIVITY	DESCRIPTION
Transcription	Activities concerning the conversion of the originally supplied 2D drawings into a format adequate to the internal design process.
2D Design	Analysis + 2D Drafting (floor plans and views).
3D Design	3D modeling + Analysis + Model checking + Model correction.
2D Checking	Geometric and conceptual compatibility analysis + Checking.
Correction	Correction of geometric and conceptual errors.
2D output	Dimensions, notes and sheet layout activities.
Quantity Surveying	Counting of masonry bricks and other wall components.
Design changing	Revisions due to change orders from the owner.

Some activity names were reported in both the 2D and the 3D methods, although in practice they reflect very different procedures. The times for every individual activity of each generic group were added up. Totals for each activity group as well as for the whole design work for both methods were obtained and compared.

4.2 EFFICACY STUDY ANALYSIS

The analysis method consisted in studying the records of the interferences detected between building systems and architectural, structural, and other building systems. Each interference record was assessed to determine if the problem could be detected using a 2D representation and the overlaying method or if it was only perceived because a 3D environment was used.
After classifying all interferences and constructability problems detected by the designer, total counts of both groups were produced, and percentages over the total amount derived.

5. RESULTS

This section presents the results obtained from the analyses over the data collected in both studies.

5.1 EFFICIENCY STUDY RESULTS

Data collected from Offices A and B in the controlled experiment were analyzed and summarized in the following graphs. Figure 1 illustrates total time for generic/aggregated activities, comparing the 2D and 3D methods.

The (2D and 3D) design, checking and correction activities had to be aggregated because many records in the Office A time sheet referred to mixed checking and correction activities, without separating individual times, making impossible to compute the total time for each of these activities. Also, the “3D design” activity includes checking and correction activities besides modeling and analysis and were also aggregated so that they could be compared to their 2D counterpart.

It can be seen in Figure 1 that, in 4 out of 5 general/aggregated activities, the 3D method took less time than the 2D method, resulting in 28.7% total time savings.

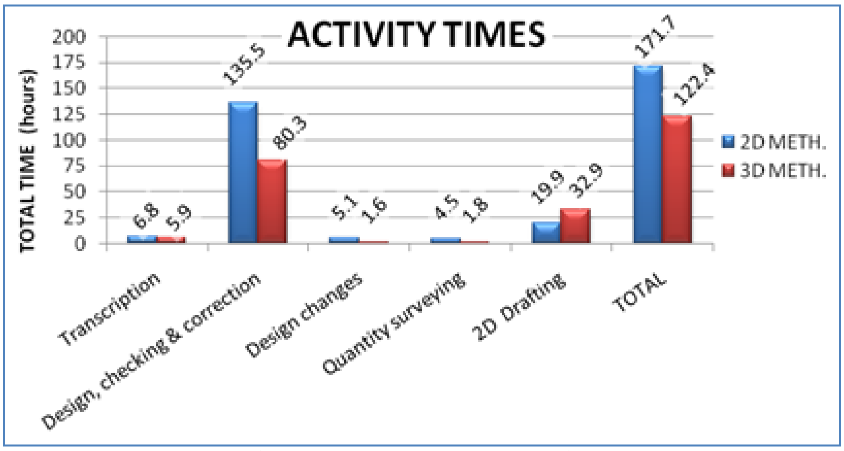

Figure 1: Total time for generic/aggregated activities for 2D and 3D methods

The activity time breakdown for the 2D Method (see Table 2) shows that checking and correction activities accounted for more than 1/3 of the total time in this method. It is important to remember that these activities do not aggregate value to the design process. Note that, in Table 2, the “2D Design” activity includes some tasks related to the “2D Drafting” activity.

Table 2: Percentage of total time for generic activities of the 2D method.

GENERIC ACTIVITIES*	**% TIME 2D METHOD**
2D Design	45.3%
Checking & Correction	33.6%
2D Drafting	11.6%
Transcription	3.9%
Design changes	3.0%
Quantity surveying	2.6%
TOTAL	**100.0%**

* See table 1

Table 3 shows a breakdown of the recorded activity times for the 3D method. The “3D Design” activity concentrates most of the time spent on the design development. From an interview conducted with the Office B designer, it could be inferred that this activity also includes frequent checking and correction tasks mingled with modeling and analysis tasks with are the core of the design process. Nonetheless, there is a significant reduction on the total time spent on checking and correction activities, which are usually carried out by a higher-graded professional.

Table 3: Percentage of total time for generic activities of the 3D method.

GENERIC ACTIVITIES*	**% TIME 3D METHOD**
3D Design	61.4%
2D Drafting	26.9%
Transcription	4.8%
Correction	2.9%
Quantity surveying	1.4%
Checking	1.3%
Design changes	1.3%
TOTAL	**100.0%**

* See table 1

Some other observations can be made from these data:

a. *Design changes were performed much more quickly with the 3D method than with the 2D one*: this is straightforwardly explained by the fact that changes in the solid model are easily done while changes in 2D imply changing drafted views, which is more complex in cognitive terms.

b. *Little time explicitly spent on checking and correction activities in the 3D method*: most problems related to geometry are immediately identified and solved during modeling by the designer because they are easily spotted. On the other hand, the 2D Design activity requires some complex or attention-demanding steps, like drawing correctly and precisely section views from floor plans and transferring wall linking points that are not necessary on the 3D method, increasing the chances for making mistakes. These errors are usually only detected later on, during the checking phase. Then they are corrected and checked again.

c. *Quantity surveying is faster in the 3D method*: using 3D CAD, brick counting is an automatic and precise task. The selection of blocks can be made by using filters. It is never necessary to count them manually, as it is, often, the procedure used with 2D techniques.

d. *Total design time is shorter with the 3D method than with 2D*: it seems the time spent on checking and correction activities on the 2D method is much longer then with the 3D method. In the last, spent time concentrates on 3D modeling and analysis. At the same time, the automation routines are more powerful when operating on 3D data as the computer has much explicit information that, in 2D, are implicit or whose link is only in the designer’s mind, like floor plans and section views or wall and brick thickness. Therefore, the computer can aid the designer more effectively.

e. *The production of the final drawings took longer with the 3D method*: as this result is unexpected, we believe it is due to the way data was collected and do not reflect the reality. This activity time can be precisely accounted for in the 3D method, as it is done exclusively at the end of the whole design process for documenting purposes only. In contrast, the 2D approach uses drawings as a tool for design analysis and solution coding. Therefore, as stated before, it is difficult to clearly separate design actions from documenting actions and to record their times in different groups. As drafting is an automated task in the 3D method, it is likely that it will be much faster than in the 2D method.

5.2 EFFICACY STUDY RESULTS

Twenty nine interferences were reported during the design phase and coordination analysis. From those, 19 were assessed as only detectable using a 3D visualization method. Figure 2 shows one of those situations where the 2D view was not enough to detect the interferences between plumbing and ceiling (purple) or between sewage (brown) and cold water (yellow) pipes. The interferences are rather evident in 3D (see Figure 3).

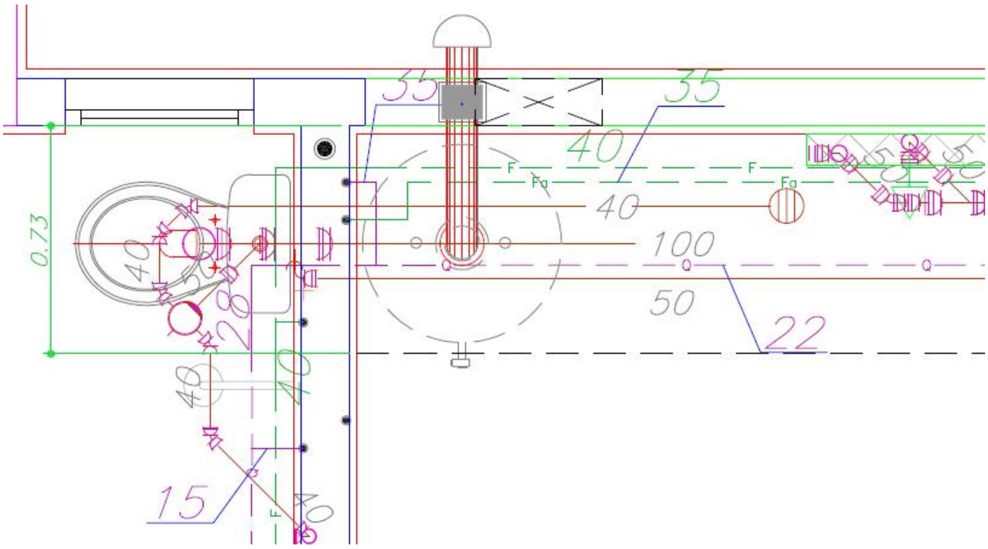

Figure 2 Some interferences that could not be detected in 2D.

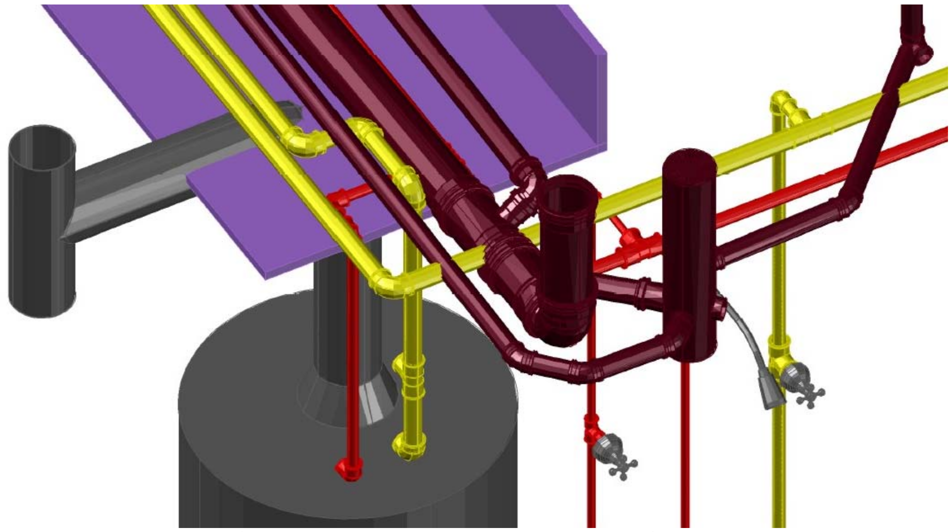

Figure 3 Interferences in building systems represented in figure 2 are evident in 3D

6. CONCLUSIONS

Although the conclusions that can be taken from this study are limited as it dealt with only two projects, one can say that it provided compelling evidences of the greater efficiency and efficacy of the 3D approach over the 2D-based method for design coordination.

Overall, the 3D-based method was almost 30% more time efficient than the traditional 2D-CAD process. Furthermore, only a small fraction of its time is devoted to the non-value-adding checking and correction activities while with the 2D method those amount to about 1/3 of its total time. Since Lean Thinking seeks to eliminate all non-value added steps (Soto, 2007), this fact is worth considering when it comes to optimizing construction design processes. The required amount of time in these activities is probably due to the abstract nature of the 2D representation which demands longer times for its interpretation. Also, it is more error-prone requiring corrections and further checking.

Quantity surveying is done quicker in 3D because this task is easily supported by the software. Design changes are also performed faster as they do not require modifying 2D drawings, which are produced only at the end of the 3D design process.

Regarding efficacy, the study reported here shown that the improved visualization attainable by the 3D method allowed much better results than 2D for detecting interferences. Most of the problems which could only be identified in 3D were related to deficiencies of the 2D representation itself, categorized by Ferreira and Santos (2007) in 5 types (see Table 4).

Most of these limitations are not inherent to the 2D representation itself, but they occur as a consequence of the current professional practice. In the 3D method used in this study, all components are modeled at their true size and adequate level of detail for detecting relevant geometrical interferences. By doing so, no symbols are used and hard interferences manifest as intersections among solids. No fragmentation takes place as the 3D representation is unified. All that contributes to increased interference detection efficacy.

Table 4: Deficiencies of the 2D representation

2D DEFICIENCY	**DESCRIPTION**
Ambiguity	The same representation may be interpreted in different ways.
Symbolism	A component is represented by a symbol whose dimensions are not related to the object it represents.
Omission	Information is omitted from the drawing as a way to make it cleaner or because such information could be presumed.
Simplification	A representation is a simplification of the object it stands for. It is similar to Symbolism, but its shape preserves some true dimensions (like pipes represented by single lines).
Fragmentation	Occurs when the information necessary to fully understand the geometry is

	scattered in several separated views (sometimes even in different sheets) like floor plans and sectional views.

Another worthwhile observation regards development costs. Although data about this matter was not collected in this study, it is supposed that the detailed masonry design and coordination cost about the same with both methods. This is because, even though the total design time is shorter with the 3D method, it demands a higher-wage professional and more expensive and powerful computer equipment (software costs are the same, as 3D capacities are available on the software typically used for 2D-based design). On the other hand, the costs of rework and diminished productivity due to interferences being detected later or even only on site because of the lower efficacy of the 2D method for spotting them on the design phase are much higher.

We hope mainstream AEC design may soon evolve to 3D environments, the only way the full potential of Information Technology can be realized in this realm. The adoption of BIM tools may be a perfect shortcut to reach this much needed condition.

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