Automation in Construction 19 (2010) 148–159

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

An evaluation of the applicability of 4D CAD on construction projects

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ARTICLE INFO

Article history:
Accepted 13 November 2009

Keywords:
4D CAD
Commercial projects
Infrastructure projects
Benefits
Visualization
Constructability
Project progress review

ABSTRACT

4D CAD models that integrate physical 3D elements with time, have been used to visualize construction processes in several projects worldwide. 4D models have been used and have been shown to have benefits over processes that span the entire lifecycle of a project such as collaboration with stakeholders, making design decisions, assessing project constructability, identifying spatial conflicts in construction and so on. Despite these benefits, several organizational and project-specific barriers have hindered the widespread adoption of 4D CAD. In order to reconcile the theoretical benefits of 4D models with the practical difficulties faced in implementation, there is an urgent need to explore the *implementation* of 4D models on construction sites as well as the *perceptions* of intended users/beneficiaries towards this implementation. This paper aims to address this need and contribute to our understanding of how 4D models must be introduced, positioned and implemented on construction sites, so as to maximize both their acceptability and their usefulness. We describe two 4D models of infrastructure projects and two 4D models of commercial projects that have been built and implemented. Through a process of structured and unstructured interviewing the paper gauges the response of project participants across various organizational levels on each of these projects as to the usefulness of 4D in project planning and control. Through qualitative and statistical analysis of the data we establish that 4D CAD is likely to be most beneficial in the project shaping or planning stage and in the construction stage. In the project shaping stage, 4D CAD is likely to be particularly useful in communicating construction plans and processes to clients, while during the construction phase, 4D CAD is likely to be particularly useful in comparing the constructability of work methods visually in order to detect conflicts or clashes, and as a visual tool for contractors, clients, subcontractors and vendors to review and plan project progress. Further, upper management and site workers are more likely to use and derive benefits from the visualization of processes using 4D given their lack of site related knowledge or skills, while construction professionals who are more construction-savvy are more likely to appreciate and benefit from the analytical and planning aids that 4D simulations provide during the construction phase. However, it is likely that despite these benefits 4D CAD models might not diffuse through the construction industry unless 4D modelling and analysis is integrated into existing project planning approaches. The paper concludes with a brief discussion on future 4D software development that seeks to bring about such integration and leverages the benefits of 4D CAD to bring about improved operational efficiencies on construction sites.

1. Introduction

4D CAD models integrate 3D geometry with time as the fourth dimension [16]. Any building component in a 4D model will contain geometric attributes that describe its 3-dimensional shape. In addition, a time attribute that indicates the start and finish time of the construction of this element will also be attached to this building component. A 4D model of a structure can therefore be used to graphically simulate the sequence of construction operations, thereby providing the operator with a virtual, visual understanding of the construction process [5]. 4D models aim to augment and integrate traditional planning aids such as 2D drawings and CPM schedules. Such aids are often cumbersome to interpret as they contain a multitude of details, and require significant expertise to synthesize. 4D visualizations are simpler representations of the development of the project and can be used by a wider variety of project participants at varying levels of skills and experience.

4D CAD has been used by planners, designers and engineers to analyze and visualize construction projects in order to make design related decisions, plan construction operations, analyze the constructability of a project plan [6], develop cost estimates, manage resource requirements [2,19] and to communicate and collaborate with clients and other project stakeholders [13,18]. Scholars have studied the use of 4D CAD to optimize site layouts [25], improve site logistics and the space

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doi:10.1016/j.autcon.2009.11.015

for work execution [1,10], to evaluate various alternative construction schedules [22] and to train inexperienced planners and workers [11]. Several case studies of the implementation of 4D CAD on construction projects have also been documented (e.g. [4,8,9,14]).

As Hartmann et al. [7] point out, prior research has shown that significant benefits in terms of time and cost savings can result through the systematic use of 4D technologies on construction projects [16,24]. 4D models have proven particularly helpful in projects that involve multiple stakeholders, and which face space constraints on the site [5]. 4D models have been shown to enable a diverse team of participants to collectively make decisions on a project and improve the constructability and execution strategies, so as to realize gains in site productivity [15]. In addition, case studies have indicated that 4D models help identify design conflicts prior to construction, help bridge gaps in skill and knowledge among workers, increase cost control, detect time–space conflicts and ensure lower rework rates and requests for information during the course of the project [15].

Despite these benefits, 4D CAD technology has not been widely embraced by the construction industry worldwide [23]. Many reasons have been attributed for this state of affairs. Khanzode and Staub-French [15] highlight the fact that 4D modelling on an actual project is a complicated process that requires coordinated effort. Taylor [20] and Taylor and Levitt [21] point to the fragmented nature of the construction industry to explain the difficulty in large-scale diffusion of new technologies, while Barrett [3] cites industry-culture based factors such as the reactive nature of the construction industry that hinders the proactive adoption of sophisticated technologies such as 4D CAD by practitioners.

In the current day context, construction companies stand to benefit if they are able to effectively leverage 4D technology to improve their performance. A large amount of infrastructure is being planned and built in developing countries, and is being repaired and re-built in developed ones. Despite the vagaries of macroeconomic cycles, many construction companies have over-flowing order books consisting of complex non-routine projects. It has therefore become imperative for construction companies that wish to survive and grow in today's competitive environment to evolve newer project management paradigms, and to focus on tools that help improve operational efficiencies, for two reasons. First, given the large volume of projects that companies are undertaking, improvements in efficiency can translate into windfalls in terms of savings and profits. Second, in order to handle this new challenge of having to manage multiple, complex projects under severe time and resource constraints in the current environment, construction companies require the use of sophisticated planning tools and innovative, streamlined construction processes so as to ensure that all projects are completed on time, within budget and to acceptable standards of quality.

On the one hand it is likely that 4D models and their associated benefits in terms of improved communication, work space planning and project time and cost control can be effectively used to improve operational efficiencies in the construction industry. However, on the other hand, 4D CAD has not been systematically or rigorously adopted in the construction industry. In order to reconcile the theoretical benefits of 4D models with the practical difficulties faced in implementation, there is an urgent need to explore the *implementation* of 4D models on construction sites as well as the *perceptions* of intended users/beneficiaries towards this implementation. An in-depth examination of these issues can help practitioners and researchers understand how 4D models must be introduced, positioned and implemented on construction sites, so as to maximize both their acceptability and their usefulness. This paper attempts to start to address this issue by using case study evidence on actual construction projects to understand the challenges of and perceptions towards implementing 4D CAD on construction projects.

In the next section we present specific research goals that we aim to achieve in this paper. Following this we discuss the methodology that we will use to achieve these goals. We then describe and statistically evaluate the 4D simulations that we have built and applied on construction projects in India, and their usefulness. We will then conclude with a discussion of these results and suggestions on how 4D CAD technology can be adapted to the construction environment.

2. Research goals and methodology

This paper seeks to address two research goals (RG) that will help bridge some of the gaps identified in the previous section. These are

> *RG1*: To develop an understanding of *the conditions under which* 4D CAD usage might be most beneficial in construction (including but not limited to identifying the stages and types of projects where 4D is likely to be applicable as well as potential users of 4D technology within the project organization), and the consequent benefits to the project.
> *RG2*: To develop an understanding of *how* 4D CAD can be used in the construction industry and how this technology can be integrated into, and help modify current construction processes.

In order to address these research goals, our methodology draws upon a framework proposed by Hartmann et al. [7]. In analyzing the areas of application for 3D and 4D models on construction projects, Hartmann et al. [7] analyze and point out the limitations of several frameworks for categorizing 3D/4D model application areas. Combining these frameworks and addressing these limitations, they establish a new categorization scheme that we will adopt in this paper that looks at the application of 3D/4D models across three *phases* of a project—the Shaping or Planning phase, the Design Phase and the Construction Phase.

In addition to evaluating the applicability of 4D CAD across each of these phases in construction projects, we introduce a second dimension to this framework that categorizes the *type of project*. Although there is a wide variety of available project types, this paper will focus specifically on two project types—viz. commercial buildings and infrastructure projects. Each of these project types present different challenges with respect to levels of complexity, difficulties in organization, resource and manpower requirements and legal/institutional interfaces. As a result there is a need to analyze the impacts of 4D models on each of these project types separately.

Finally, we also incorporate a third dimension that categorizes the *type of user* of the 4D CAD system. We consider three types of users—(a) Upper Management or high-level executives of firms, (b) Construction Professionals who predominantly spend time at sites such as project engineers and project managers and (c) Workers such as site superintendents, foremen, crew leaders or skilled workmen. These three levels of users traverse the spectrum of personnel on a construction site. Although not all of these personnel are likely to build 4D models, they all have the potential to use and benefit from 4D models. For instance, upper management in both the clients and contractors organizations who do not have the time or resources to undertake detailed analysis of project documents could use 4D models to visually understand the sequence of construction and the challenges involved, construction professionals could use 4D models for detailed planning, while workers might derive benefits from visualizing the tasks that they are required to perform. It would therefore be pertinent to evaluate the applicability and benefits of 4D CAD across all of these levels of personnel. Fig. 1 below presents our research framework.

2.1. Research methodology

For the purposes of our study we selected four projects that were being built in India, two each in the Infrastructure and Commercial

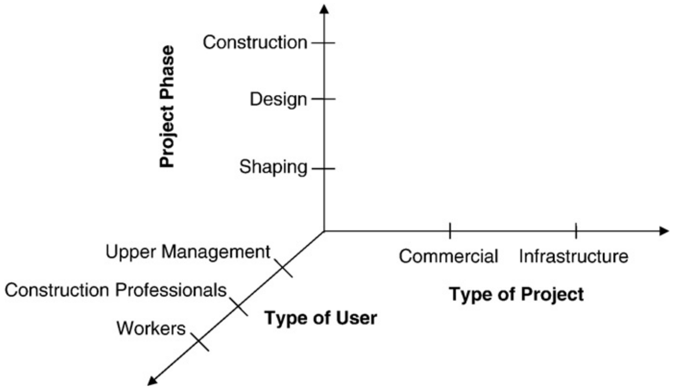

Fig. 1. Research framework.

construction sectors. We selected projects that were significant in size and scope, and which used well-known and globally available materials, technology and construction practices, so as to ensure that the construction processes that were modelled through 4D could be applicable in other countries with similar environmental contexts as well. We used a combination of a qualitative and a quantitative approach. Our methodology was to first model projects in 4D and to then analyze their implementation on projects qualitatively through interviews with project personnel. However, qualitative research conducted in this manner can only provide propositions that need to be tested through further research. We therefore developed hypotheses both from our qualitative analysis as well as from findings in the extant literature, and then attempted to statistically validate these hypotheses using a survey. As Leonard-Barton [17] notes, using multiple research techniques within the same study can lead to greater rigor in the research and confidence in the findings, since “the advantages of using one method balance out the disadvantages of other methods”.

Our first task was to build detailed 4D CAD models for each of these four projects. The creation of each 4D model represented 2 man-weeks of effort that included obtaining 2-dimensional drawings and construction schedules, creating 3D models, integrating these models with the schedule to create 4D elements and developing the simulation. Each of these 4D models was shown to personnel in each of the three user levels that we had identified and their opinions were ascertained mainly through a mix of structured and open-ended interviews.

Construction had commenced in all four of the projects that we had modelled. As a result, we were unable to effective gauge the applicability of 4D CAD to the design and shaping phases of the project from these interviews alone. We therefore used a survey instrument to assess the applicability, usefulness and shortcomings of 4D CAD in the shaping, design and construction stages of engineering projects. A series of hypotheses were crafted based on our qualitative findings and the existing literature, taking into account various sub-processes and stages involved in the shaping, design and construction of projects in India. A total of 63 individuals were interviewed through our survey and the hypotheses were quantitatively tested using standard statistical techniques to establish their significance or to disprove them.

This data collection and evaluation methodology, using a mix of qualitative, quantitative and simulation techniques allowed us to obtain some amount of generality with regards to our findings, since our findings were not limited to a particular project instance, but encompassed different projects, phases and users. Furthermore, this approach also allowed us to tease out the nuances of the implications of 4D CAD in construction. We were therefore able to study say, specific ways in which 4D systems could be used in the design phase of a project as opposed to limiting our findings to more general comments on the use of 4D CAD on projects as a whole. In this manner we were able to answer our stated research goals of understanding where and under what circumstances 4D models can be usefully applied to construction projects so as to accrue benefits in terms of project performance.

We now first describe the models that we built, before describing the hypotheses that we formulated around these models, the parameters that we evaluated and the results of our analysis.

3. Models

3.1. Infrastructure model 1

The first infrastructure project that we modelled was the construction of a Cargo Berth in a typical port in the South of India. In order to model this project we first modelled the pile driving activities near the shore in 4D. The pile driving sequence that we chose to model consisted of boring piles, lowering pile reinforcement and pouring concrete for the piles. As the piling work finished, the construction schedule indicated that work on in-situ cross beams and longitudinal beams would start. Also, the excavation and dredging of the earth between and around the piles would also start after completion of the piling activities. After modelling the dredging activities we then modelled the slope protection works in two parts—construction of a rock bund and slope protection through the use of smaller rocks. After this, we then modelled the filling of the excavated portion and the concreting of the retaining wall. Following this we modelled the process of deck construction through the use of pre-cast slabs, as envisaged by the construction methods planners. After constructing the deck, the placing of a second slope protection layer and backfilling were modelled. We concluded our model of the construction sequence by modelling the fixing of fixtures on to the cargo berth.

Since the process of construction of a cargo berth is largely mechanized, we modelled the use of equipment in our 4D model. For instance, we modelled the use of dredgers in the dredging activity as well as the use of cranes for placing the pre-cast deck slabs, and so on. Through this approach, we hoped to provide visual images of equipment use and location throughout the construction process in order to allow site personnel to assess equipment-based constraints on site, during construction.

Fig. 2 provides a snapshot of the 4D model that was built and shows the construction of the deck in progress.

3.2. Infrastructure model 2

The second infrastructure project that we modelled was the construction of a Breakwater, a schematic diagram of which is shown in Fig. 3 below.

In order to model the construction of this project, we first modelled the placement of a primary filter which consists of material in the 0–250 mm range, and which is to be transported onto a split barge and then dumped on to the sea. Subsequently, once the primary filter has been placed in the required profile, the next layer called the ‘core’ layer is placed. Material in this layer is much bulkier and can weigh as much as 500 kg. Once the core layer was modelled, we then modelled the placement of a 500 mm slope filter on the side of the breakwater that faces the harbour. A geo-textile was then modelled to be laid above the slope filter on the harbour side. We then modelled the placement of a second slope filter layer of 500 mm thickness on top of the geo-textile layer. As per the construction sequence, the next activity was the placement of a secondary armour layer of rock on the side slopes of the core, using an excavator. The construction schedule then indicated that accropodes of varying shapes would need to be placed on the breakwater. We modelled the placing of these accropodes in such a manner that the lighter accropodes were placed

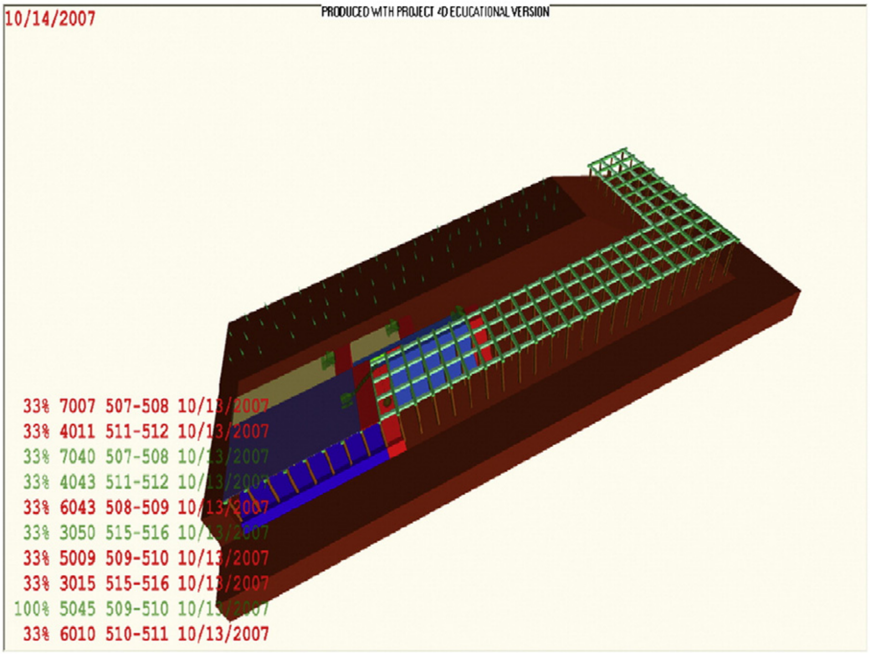

Fig. 2. Construction of the deck.

near the shore and as the depth of water increased as one moves away from the shore, the size of the accropodes would also increase. Finally, after modelling the placing of accropodes, we modelled the construction of a wave wall on top of the breakwater to avoid the entry of rising waves.

As in the previous model, the use and position of equipment was also modelled. Fig. 4 shows a snapshot of the 4D model that was built. In this figure, the secondary armour is being constructed.

3.3. Commercial model 1

The first 4D model that we developed in the commercial space was that of an academic department. This educational building consisted of a ground floor and two additional floors, covering an area of approximately 1600 m^2. Fig. 5 shows a schematic layout plan of the building.

In order to develop a 4D model for this structure, we first developed a site layout model that included a site office, a storage yard, the position of the concrete mixer, the barbending and cutting yard, and material storage facilities. Standard construction procedures were adopted for the development of the building. Site excavation was first done in order to construct isolated footings. After excavation, the placing of reinforcement for the footings was modelled followed by concreting for the foundations. Next, the construction of the ground floor columns was modelled. Each column was modelled as consisting of three pours in order to accurately represent the procedures followed on site, and the placing of the columns was staggered to conform to the construction schedule. Following this, lift walls and the staircase on the ground floor were modelled. After this, the construction of the beams and the first floor slab was depicted in 4D. The same procedure was then repeated on the first and second floors. After the completion of the columns, beams and slabs on all three floors, the construction of the overhead tank and the lift machine rooms on the terrace were modelled. As construction of the higher floors progressed external brickwork, electrical and HVAC work, and painting on the lower floors were also modelled in accordance with the schedule.

Fig. 6 shows a 4D model snapshot wherein the top floor slab is being constructed.

3.4. Commercial model 2

The second 4D model that we built in the commercial space was of one office building in a large office campus. A series of 6 buildings were planned for the entire campus that was being built on a 70 acre parcel of land. 4D models were built at two levels for this project—an initial 4D of the external structure of the building was first built. A second, more detailed model of the construction of one floor of the building

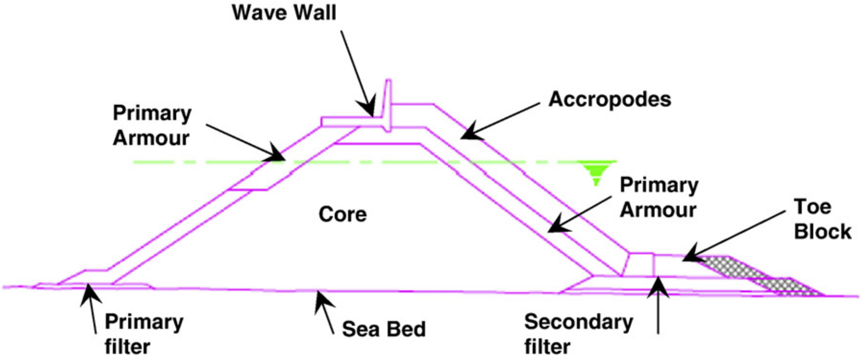

Fig. 3. Typical cross section of a breakwater.

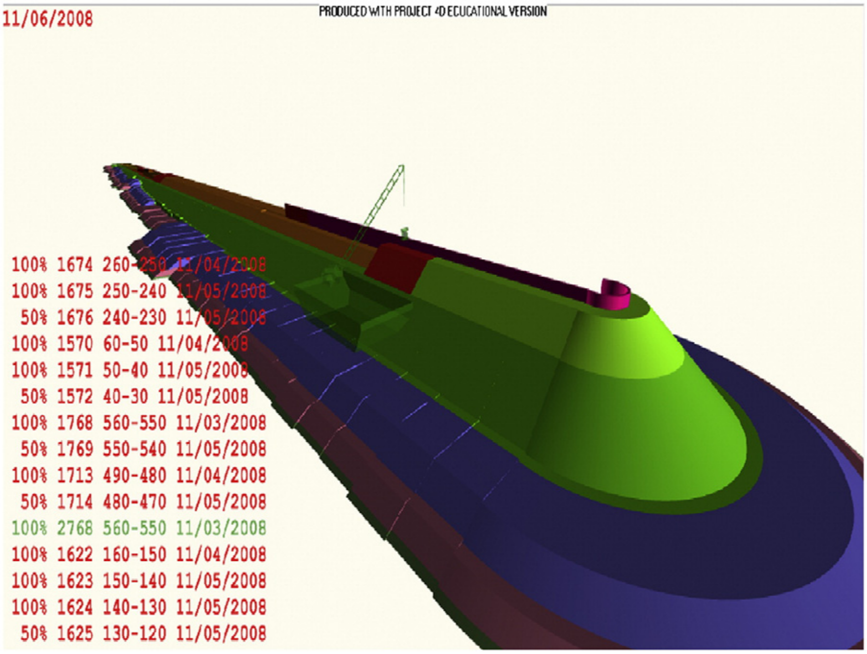

Fig. 4. Construction of secondary armour.

including false ceiling works was also built in order to provide both micro and macro perspectives on the construction of this building.

The building footprint consisted of two wings, each of which had seven floors including the ground floor. These wings were built in parallel. In between these wings, a central core was built that connected to both wings on each floor. The central core housed the elevators, the reception area, a library and the restrooms. A complex arrangement of trusses known as the ‘spine’ formed the roof elements on top of the core and the wings.

In order to build the 4D model for the macro structure, the foundation work was first modelled. The ground floor columns were then modelled in 4D followed by the ground floor slabs for each of the wings. Following this, the columns and the slabs for each of the subsequent floors were also modelled. As the construction of each of these wings was being modelled, the construction of the core started, albeit with a lag. As the higher floors were being constructed, interior and façade work was undertaken on the lower floors. After the construction of the core and the two wings the placement of the truss elements and the construction of the spine were modelled. Fig. 7 shows a 4D snapshot of the construction of the building and depicts the installation of the roof trusses.

For the 4D model of the construction of the interior of a floor, a series of activities were considered. The above-false-ceiling works were first modelled as per the construction sequence adopted on site. This consisted of modelling the electrical wiring, followed by modelling the installation of the AC ducts. Next, the installation of the sprinkler system was modelled. Along with the sprinklers, the fire protection systems were installed and the electrification was done.

In parallel with the above-false-ceiling works, other internal works such as internal screeding, erecting hand rails on the corridors,

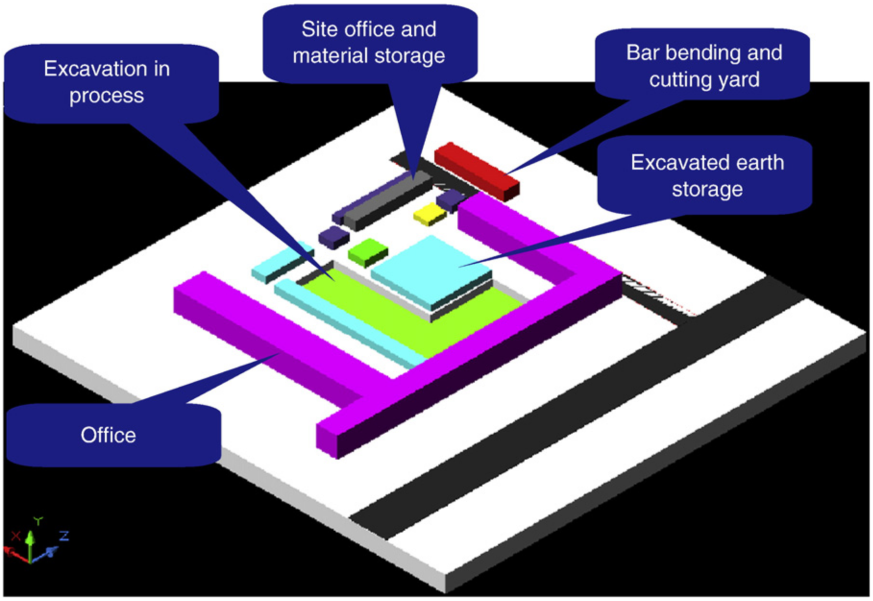

Fig. 5. Schematic plan of the building layout.

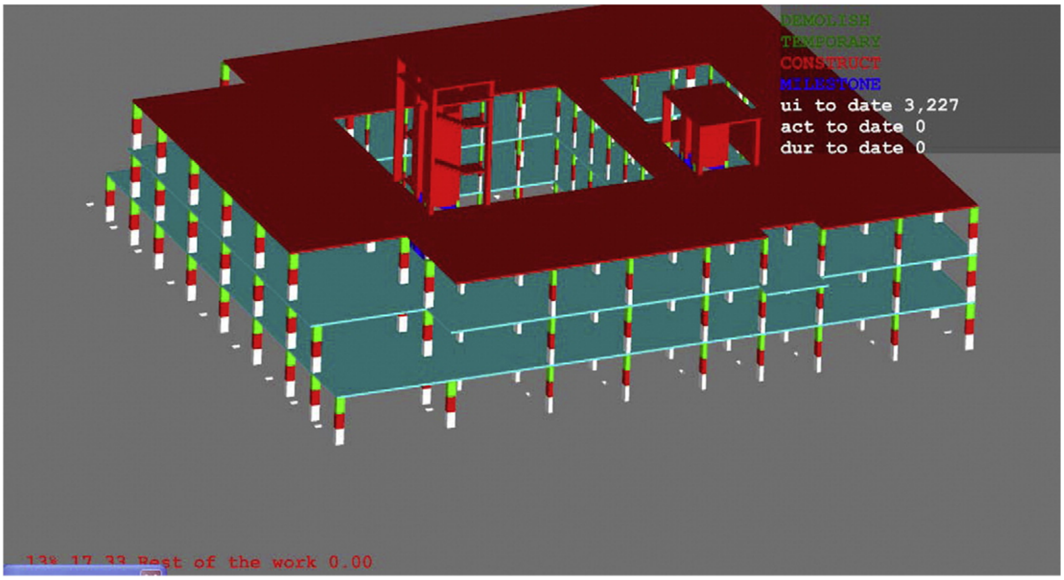

Fig. 6. Construction of second floor roof slab.

installing structural glazing, painting, installation of flooring, and installation of partitions, doors, fixtures and signages were also modelled. Most of these activities occurred in parallel and were modelled thus.

Fig. 8 shows a snapshot of the installation of sprinklers across a typical floor.

4. Analysis

4.1. Qualitative results

The various 4D models described in the previous section were built and used by several organizations in each of the sites indicated above. The process of developing a 4D model and using it led to several interventions being made to the project planning process. Through observing and documenting these interventions, we were able to arrive at several anecdotal, but practical benefits of using 4D CAD on real-world construction projects.

On the Cargo Berth project, most of the construction took place underwater and therefore 4D CAD proved immensely useful in helping the project team visualize the sequence of construction activities. 152 piles had to be constructed to support the berth. A 4D CAD visualization of the construction sequence of installing these piles helped the project team design a process where pile driving could be carried on in parallel in different locations, while ensuring that ‘fronts’ or space for equipment movement was not constrained. The initial plan had called for piling work to start from one end with the help of 15 winches. However, the 4D model showed intense spatial conflicts with this approach. As a result an alternative plan was developed wherein the entire pile driving operation was started at three parallel zones with five winches in each zone.

The breakwater project was also very equipment intensive and the 4D visualization allowed planners to ensure that excavators, transit

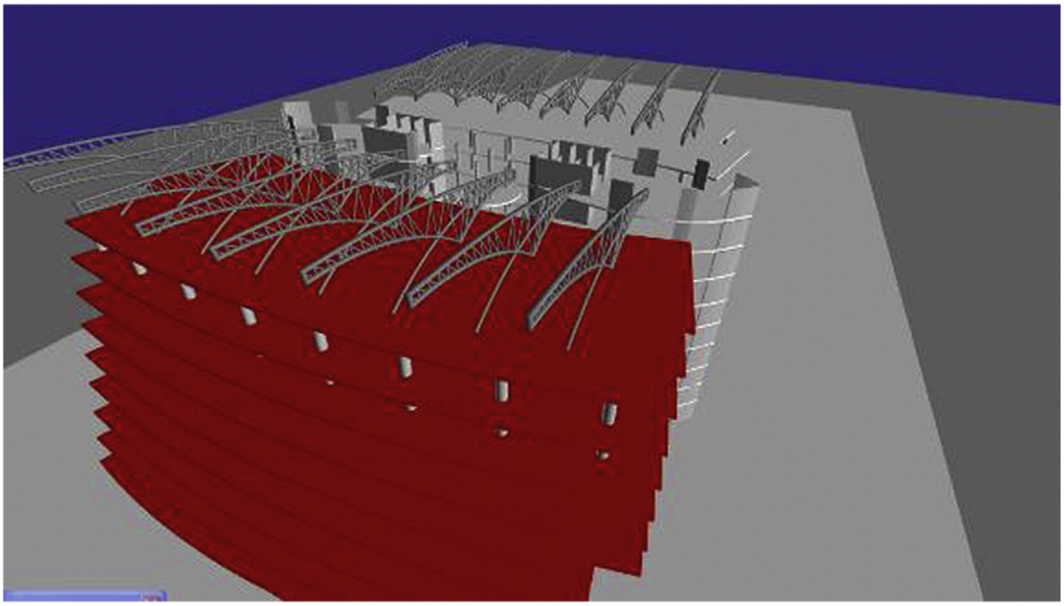

Fig. 7. Installation of roof trusses.

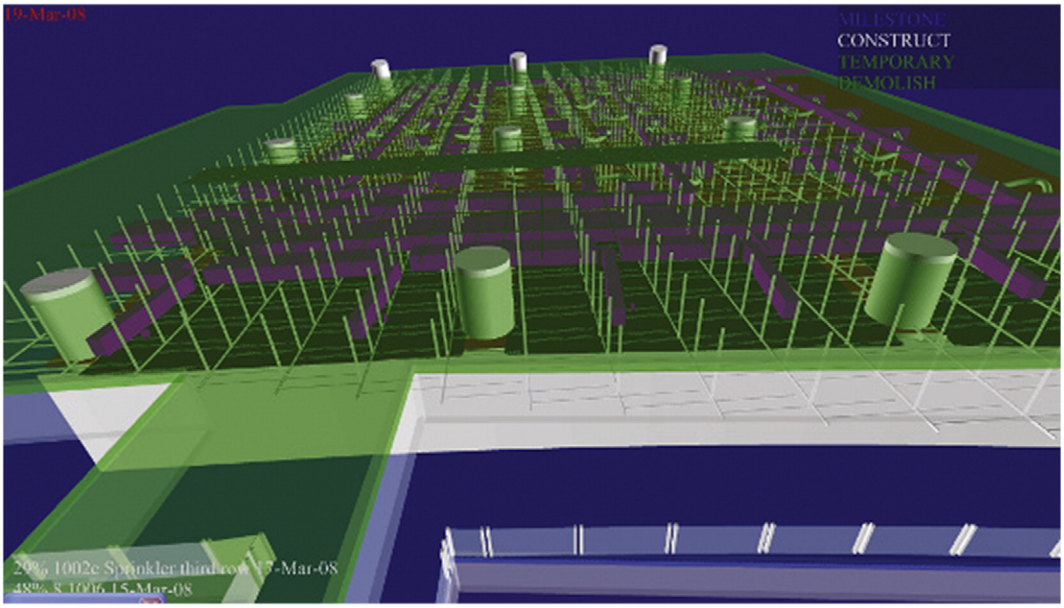

Fig. 8. Sprinkler installation.

mixers and trucks used to move materials did not interfere with one another. In addition, planners on this project were able to use 4D simulations to select equipment. For instance, the maximum allowable boom length and reach of a crane was visualized through the 4D simulation keeping dynamic, temporal physical constraints in mind, and an appropriate crane was selected. While viewing the 4D simulation for the breakwater construction, planners noticed that it was not possible for the crane barge carrying the accropodes for the primary layer to come too close to the breakwater due to the lack of draft available. Further, the reach of the crane mounted on the crane barge was not sufficient to place accropodes via the sea. As a result of this insight obtained through visual simulation, the method of placement of accropodes was changed from sea-mode to land placement.

4D CAD proved to be an extremely useful communication tool on the academic building project. Most workers spoke only Tamil, while the project engineer spoke only Hindi and English. 4D models were therefore used to communicate with the workers and enlighten them on the process by which the work was to be done, as well as the level of detail of the finishes required and so on. Also, while visualizing the 4D model, planners for this project felt that while the civil engineering operations were shown in good detail, the lift installation and other MEP related activities were hardly visible. This then led to an inspection of the schedule, which the planners found to be incomplete. 4D CAD therefore allowed the planners to revisit and create a more robust schedule that accurately captured the various project activities.

The 4D model of the commercial building project showed a period of two months where very little activity was visible. The project management team therefore deduced that the existing schedule was sub-optimal and were able to further optimize and speed up the schedule. Also, when modelling the false ceiling works, the planning team observed through the 4D model that in one area of a typical floor there was a physical conflict between the installation of AC ducts and the installation of the sprinkler systems. This allowed the planners to change the positioning of the ducts and the sequence of installation to eliminate this conflict beforehand, so that the actual implementation could proceed smoothly.

These anecdotes show that the process of building and viewing a 4D model yielded useful insights that helped construction planners optimize on site processes. 4D CAD also proved to be a useful visualization and communication tool. However, there were also several limitations and challenges that we encountered. First, building each 4D model involved integrating a variety of drawings. We found that the drawings we required were sometimes available only in paper form, and therefore we needed to expend extra effort to transform these drawings into electronic form. In addition, the drawings were spread over various divisions and geographic locations. Collating them presented a challenge and required extensive back-and-forth communications between the project sites and our research team. Second, participants varied in their perceptions on the level of detail to which the 4D model was to be made. In the commercial office space project in particular, we encountered a situation where a civil engineer working for the client asked for a model at a higher level of abstraction that what we had built, while an electrical engineer wanted to look at the model in greater detail. Building models at various levels of detail to satisfy the needs of all project users is likely to be very time consuming. However, it is likely that such a strategy must be explored to ensure that 4D models benefit a broad range of project personnel since a one-size-fits-all model is unlikely to cater to everyone's needs. Third, the quality of the visual representation of the 4D models differed from a video-graphic representation of the actual construction processes on the site. As a result, many of the project participants that we interviewed were unable to identify with the simulation immediately. We had to serve as 'interpreters' and explain the evolution of the 4D simulation. However, once explained, most participants were able to interpret the simulation and brainstorm on managerial decisions that could be made. Finally, in the initial stages of model-building, we were met with some skepticism. However after the models were built and demonstrated, many participants became more inclined to discuss the models and their implications on construction practice. Although our qualitative analysis indicated that 4D CAD was useful to the construction industry, these limitations highlight some of the challenges involved in implementing 4D on project sites.

Our next step was to quantify the magnitude of impact and the extent of usefulness of 4D models on Indian projects. In order to do so we then supplemented our qualitative analysis with a quantitative survey of the effects and benefits of 4D CAD on Indian construction projects.

4.2. Quantitative results

Based on both the benefits of 4D CAD that have been documented in the existing literature on the subject and the qualitative anecdotes that we encountered during our implementation experience, we crafted four hypotheses on the benefits of 4D CAD. These hypotheses are presented below:

- H1: In the project planning or shaping phases, visualization of project processes using 4D CAD will lead to significant advantages and reduction in rework and extra costs.
- H2: 4D CAD models can be used in the design phase of projects to communicate across disciplines and effectively resolve design conflicts.
- H3: 4D CAD models can be used in the construction phase of projects to plan construction processes, evaluate constructability, optimize resource utilization and review project progress in order to effectively plan and monitor the project while preventing delays.
- H4: 4D CAD can be used for advanced functions such as dispute management and delay analysis, project trouble shooting and alternative comparison, in order to optimize project processes and profitability.

The first three hypotheses evaluate the benefits of 4D CAD along the 3 main dimensions of the framework devised by Hartmann et al. [7]—viz. planning, design and construction, while the fourth hypothesis investigates the broader applicability of 4D models to advanced project management functions.

In order the test these hypotheses, we devised a survey instrument that we administered on participants in each of the four project sites that we visited in order to create 4D models. A total of 63 participants were surveyed. Table 1 below provides information on our sample.

Survey questionnaires were not mailed out. We administered the surveys personally. In addition, we had approached and had been given permission to conduct our study by the clients of each project. Project participants had been notified of our research and had been encouraged to participate in it. As a result, our response rates were higher than if we had remotely administered a survey.

With regards to Upper Management, we restricted ourselves to executives in operations-related or marketing-related functions from both the client's and the contractor's organizations, working in the geographical zone where the project was located. We conducted our surveys at both the project sites as well as at corporate headquarters. Since the sample pool was small, our strategy was to interview all respondents. However, some of our target respondents had heavy travel schedules and as a result we were unable to interview them.

We implemented the surveys on construction professionals and workers on the jobsite. Once again since there were only a limited number of individuals in the category that we termed ‘construction professionals’, we attempted to talk to all of them. However, some of these personnel were unavailable during our visits. The workers category was the largest among the three categories of users that we surveyed. It is difficult to estimate the target population of this category, since the number of foremen, supervisors, etc. varies as the project progresses through various phases. We estimate that at the time of our study, around 80 such employees were present on the projects that we observed. Daily laborers, semi-skilled and unskilled workers who form a large percentage of the Indian workforce, were not part of this category and were not interviewed. Several people in the ‘workers’ category did not speak English or the regional languages that the authors spoke. These people were excluded from the survey. We attempted to speak to as many other workers as possible, while trying to survey a comparable number of people as compared to the other user categories.

Table 1
Sample summary statistics.

User group	Respondents	Target sample size	Response rate
Upper management	18	28	64%
Construction professionals	20	24	83%
Workers	25	80	31%
Total	63	132	47.7%

Most of our respondents at the Construction Professional and Worker level had at least 5 years of experience on similar construction projects. However, none of our respondents had used or seen a working implementation of a 4D CAD model. Hardly any of the Workers or Upper Management respondents knew of the use of 4D CAD in construction. More than half of the Construction Professionals had heard of 4D either through professional conferences or trade magazines, but had no experience using or analyzing the tool.

All questions in the survey were administered using a 5-point Likert scale to capture responses (5 indicated a high degree of 4D CAD usefulness, 1 indicated the complete lack of usefulness of 4D with 3 being the mean point for each question). In order to ascertain the usefulness of 4D CAD as a visualization and communication tool in the planning phases (H1), participants were asked questions relating to the applicability of 4D CAD in pre-bid meetings, client–contractor interfaces such as meetings between project managers and high level client executives, and the usefulness of the means of representation of the 4D model as opposed to conventional planning techniques.

In order to ascertain the usefulness of 4D CAD in the design phase (H2), participants were asked questions on the potential for using 4D CAD to collaborate and communicate with different design specialties, as well as the potential for 4D CAD to provide insights for architectural, structural and MEP design.

To test H3—viz. the usefulness of 4D CAD in the construction phase, participants were asked to rate the usefulness of 4D CAD for schedule review meetings, preparation of progress reports, evaluating construction methods and constructability, planning for cash flows, materials, equipment and labour, collaborating with subcontractors on the site and controlling and monitoring project progress.

Finally, participants were asked to rate their perception of the usefulness of 4D models for dispute resolution, alternative comparison and delay analysis in order to evaluate 4D CAD's applicability in advanced project management functions. The survey consisted of a total of 27 questions spread across the four hypothesis categories.

Responses to questions were grouped according to respondent type as well as hypothesis. An analysis of variance (ANOVA) was done to ascertain whether there were different responses to each of the hypothesis and to establish the relative importance of the various areas of application of 4D CAD. The ANOVA is a more generic form of the more popular ‘*t-test*’ and tests the differences or variance between the means of two or more populations. This technique compares the variances within the samples with the variance of the sample means to infer if there is any significant difference in the means of the various groups or populations considered [12].

In this paper, the mean and standard deviation of the responses within each hypotheses group was used to ascertain whether each hypothesis was individually valid. Furthermore, within group ANOVA analysis was done by user type to understand variances in the responses given by upper management, construction professionals and workers. Finally, each hypothesis was tested by examining the usefulness of 4D CAD in various sub-processes within the larger planning, design and construction environments. Within group ANOVA analysis was then conducted to establish the relative potential for the use of 4D in each of these sub-processes within each hypothesis category or project phase. The results of the quantitative analysis are presented below.

4.2.1. Results

We first analyzed the mean responses across the 27 questions that we had asked to all survey participants. Table 2 shows the ANOVA analysis of the responses received across all questions and hypothesis categories.

Table 2
ANOVA analysis across hypothesis categories.

Source of variation	Sum of squares	Degrees of freedom	Mean squares	*F*
Between	1.067	3	0.3558	2.475
Error	3.307	23	0.1438	
Total	4.374	26		

Table 4
ANOVA analysis across user types.

Source of variation	Sum of squares	Degrees of freedom	Mean squares	*F*
Between	3.97	2	1.98	0.626
Error	13.15	78	0.16	
Total	17.12	80		

For a sample of 27 responses in 4 categories, the critical *F* value for a significance level of 0.05 should be 3.03. The *F* value of 2.475 therefore indicates that 4D CAD's usefulness does not vary significantly enough across the four hypothesized project domains of Planning, Design, Construction and Advanced Project Management. The null hypothesis that 4D CAD is useful across each of these domains can therefore not be rejected. However, for a significance level of 0.1, the critical *F* value is 2.34. The *F* value of 2.45 therefore indicates that there is some variation between the hypotheses categories.

Table 3 provides information on the validity of each of the four hypotheses.

As this table indicates, all the hypotheses have been validated. The mean score for each hypothesis, and the lower end of the 95% confidence interval for this mean are all above the score of 3 (which would indicate neutrality towards the benefits of 4D CAD in each category), indicating that the use of 4D CAD can confer benefits to the project in the planning, design, construction and advanced project management domains.

However, on closer inspection it can be ascertained that the mean score for the use of 4D CAD in the project planning phase is 4.4 (out of a maximum of 5). This indicates that most respondents strongly agreed with the fact that the visualization benefits that 4D models provide in the project shaping and planning phases are very likely to favorably affect project outcomes.

Also, the mean score for the use of 4D CAD in the construction phase is 4.03. Here, respondents were of the view that using 4D CAD in the construction phase for constructability analysis and project review would yield far greater benefits than using 4D CAD for resource and cash flow planning. This is indicated by the relatively lower mean score of 3.68 attributed to the efficacy of 4D CAD models for resource and cash-flow planning. By removing these latter applications out of the analysis, the mean score of for the use of 4D CAD in the construction phase of a project for constructability analysis and project review is 4.23, indicating strong convergence among members of the construction fraternity that the use of 4D CAD can significantly contribute to process improvements in the construction phase, albeit at a slightly lower level than the potential improvements that can accrue in the project shaping phase.

The mean scores for the use of 4D CAD in design as well as for advanced project management functions such as delay analysis and dispute resolution are comparatively lower, falling at 3.88 and 3.77 respectively. This indicates, that in general, project participants see lesser benefits to using 4D CAD for design coordination or for functions such as dispute resolution, as opposed to using 4D CAD for project planning and construction control, although at an absolute level, most participants concur that the use of 4D CAD can yield benefits in design and advanced project management.

Looking at the data across the two sectors that we considered—viz. commercial and infrastructure construction, no clear demarcation appears for the first three hypotheses indicating that participants in commercial as well as infrastructure projects had similar views on the uses and benefits of 4D CAD. However, on hypothesis 4, respondents working on infrastructure projects agreed that 4D models could be used for functions such as delay analysis, alternative selection and dispute resolution, as evinced by a mean score of 4.04, as opposed to commercial projects were participants tended to be more neutral regarding the possibility of using 4D CAD for these functions (Mean 3.5).

Having completed this first level of analysis across hypotheses, we then looked at the views of various types of users—Upper Management, Construction Professionals and Workers—on the potential benefits of 4D CAD. Once again we used the ANOVA technique to analyze differences in opinions across these three categories. The mean responses of participants from each of the three user types were evaluated across the 27 questions that were asked. Table 4 shows the ANOVA analysis of the responses received across all user types.

In this case, the critical *F* value is 3.11. The low *F* value indicates that there was no significant variation in the perception of the benefits of 4D CAD across user types. However a deeper look at the data indicated that the responses were not completely devoid of any variance across these groups. The more significant variances are shown below in Table 5.

As this table indicates, Upper Management and Workers at the site and job levels rated the usefulness of the visualization capabilities of 4D CAD much higher (means of 4.42 and 4.57) than the corresponding rating given by construction professionals such as project managers and engineers (mean of 4.01). On the other hand, when considering the use of 4D CAD for planning work on site, reviewing progress, creating look-aheads and assessing constructability, construction professionals find 4D CAD to be more useful (mean of 3.82) than Upper Management or site workers (means of 3 and 3.14). The latter regard these applications of 4D CAD as not being particularly beneficial to their roles and the overall goals of the project as indicated by the mean responses that are close to the neutral value of 3.

Finally, we also analyzed the relative usefulness of particular applications of 4D CAD within the larger hypotheses groups. In order to do this, we calculated ANOVA measures within each hypotheses group to understand whether there were certain applications that were either particularly useful or inapplicable within the various

Table 3
Analysis of hypothesis and their sub-parameters.

Parameter	Mean value (Max value = 5)	Standard deviation	95% Confidence Interval for mean
H1: Usefulness of 4D CAD in planning	4.40	0.26	4.08–4.72
H2: Usefulness of 4D CAD in design	3.88	0.35	3.56–4.2
H3: Usefulness of 4D CAD in construction	4.03	0.41	3.76–4.3
H4: Usefulness of 4D CAD in advanced project management functions	3.77	0.46	3.42–4.12
H3a: Usefulness of 4D CAD in construction excluding resource management	4.23	0.35	3.96–4.5
H3b: Usefulness of 4D CAD in resource management	3.68	0.23	3.35–4.01
H4a: Usefulness of 4D CAD in advanced project management functions for infrastructure projects	4.04	0.27	3.71–4.38
H4b: Usefulness of 4D CAD in advanced project management functions for commercial projects	3.5	0.25	3.22–3.75

Table 5
Analysis of user types and some sub-parameters.

Parameter	Mean value (Max value = 5)	Standard deviation	95% Confidence Interval for mean
Usefulness of 4D CAD for visualization for Upper Management	4.42	0.77	4.09–4.76
Usefulness of 4D CAD for visualization for Construction Professionals	4.01	0.74	3.84–4.19
Usefulness of 4D CAD for visualization for Workers	4.57	0.51	4.18–4.96
Usefulness of 4D CAD for construction planning for Upper Management	3	0.87	2.51–3.59
Usefulness of 4D CAD for construction planning for Construction Professionals	3.82	0.76	3.57–4.07
Usefulness of 4D CAD for construction planning for Workers	3.14	0.69	2.59–3.69

potential applications for shaping/planning, design, construction and advanced project management. Table 6 represents the results of this ANOVA analysis.

As this table indicates there were significant within group differences (all *F* values obtained are greater than the corresponding critical *F* value) in each of the hypotheses groups. As the earlier discussion has indicated, 4D CAD models are not considered very useful for advanced project management functions such as delay and dispute analysis on commercial projects, and are not considered adequate for cash flow and resource analysis across all sectors. However Table 7 indicates some categories or systems where 4D CAD models are considered particularly useful.

4D CAD was found particularly useful (mean value of 4.74 out of a maximum of 5, showing strong agreement) when it came to client–contractor discussions and presentations that were made to the executive levels of the client's organization in the formative stages of a project in order to obtain buy-in from clients who might not necessarily have good knowledge of construction practices. Practitioners also felt that 4D would be particularly useful in the construction stages of a project both to assess the constructability of a particular construction method vis a vis the design and existing site constraints (mean value of 4.26) and in project review meetings (mean 4.31) where construction methods could be presented, visualized and discussed, and where current progress and weekly or monthly look-ahead targets could be set and visually confirmed.

5. Discussion and conclusion

The quantitative analysis presented above indicates specific areas and roles where the use of 4D CAD is likely to be most beneficial. This study establishes that 4D CAD can deliver benefits in the areas of project shaping or planning, project design, construction planning and project management. Within these categories, it is likely that 4D CAD will be most beneficial in the project shaping or planning stage and in the construction stage. In the project shaping stage, 4D CAD is likely to be particularly useful in communicating the construction plans and processes to clients, who can then visualize the project and convey their suggestions or acceptance. During the construction phase, 4D CAD is likely to be particularly useful in comparing the constructability of work methods visually in order to detect conflicts or clashes, and as a visual tool for contractors, clients, subcontractors and vendors to review and plan project progress. Further, in terms of the usage of 4D CAD, upper management and site workers are more likely to use and derive benefits from the visualization of processes using 4D given their lack of site related knowledge or skills, while construction professionals who are more construction-savvy are more likely to appreciate and benefit from the analytical and planning aids that 4D simulations provide during the construction phase.

There do exist areas of application where using 4D simulations might consume a lot of developmental time and effort and might not result in commensurate gains. For instance, cash flow and resource management may best be left to existing accounting and enterprise resource planning systems. The absence of visual or geometric information needed to manage these items, might be one reason for there being no apparent benefits of using 4D to manage them. Similarly, in commercial projects, 4D CAD might not necessarily be appropriate in terms of conducting delay analysis and to resolve disputes since there might be disagreements over the assumptions made in the model. Such tasks may best be left to contractual mechanisms.

This analysis has shown that 4D CAD can be used on construction projects in order to improve operational efficiencies throughout the lifecycle of the project. However, anecdotal evidence garnered through our interviews indicated that construction professionals would resist using 4D CAD as a separate project management tool and would be comfortable using it only if it was integrated into existing management tools and practices that were currently followed on project sites. Several participants felt that although the results obtained from 4D simulations were useful, a large amount of effort was required to process the data generated and convert it into strategic information that could be acted upon. This presented a barrier in the adoption of the technology. There is therefore a need to develop an integrated project planning tool that can leverage the advantages of 4D simulations, integrate these results with existing project management processes and automate some of the analysis in order to speed up the decision making process.

For instance, such a tool could generate 4D models based on as-planned and as-built schedules and could generate snapshots of project progress for any given day. In this manner, differences between the plan and the actual schedule can be visualized and such snapshots can then be used as reports that can be circulated to

Table 6
Results of within group ANOVA analysis.

Group	*F* value	Critical *F* value for 0.05 significance
Usefulness of 4D CAD in planning	7.866	2.3
Usefulness of 4D CAD in design	3.925	2.3
Usefulness of 4D CAD in construction	13.77	1.98
Usefulness of 4D CAD in advanced project management functions	7.79	2.46

Table 7
Useful areas of 4D CAD application.

Parameter	Mean value (Max value = 5)	Standard deviation	95% Confidence Interval for mean
Usefulness of 4D CAD for clients to visualize, understand and commit on the construction process	4.74	0.44	4.54–4.94
Usefulness of 4D CAD for visualization for constructability review	4.26	0.7	4.06–4.46
Usefulness of 4D CAD in project review meetings	4.31	0.63	4.11–4.52

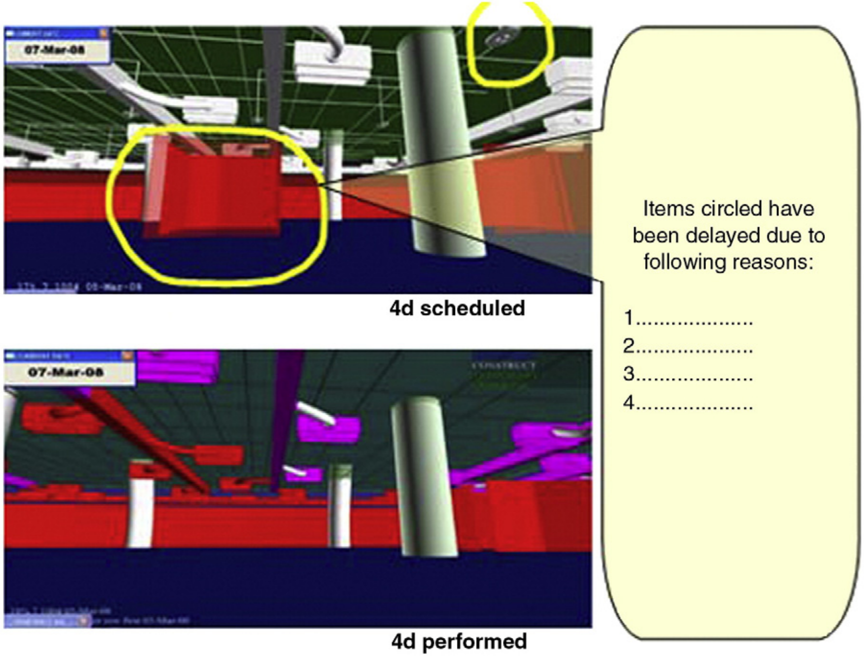

Fig. 9. Snapshot of as-planned vs. as-built differences.

appropriate project stakeholders. Fig. 9 below graphically shows how such a report might look like.

In a similar vein, 4D snapshots can be used to generate visual look-ahead targets. 4D software extensions can be developed to capture the current state of the project as well as the visual state that the project would need to attain over the next week or month. Automating this process can lead to the generation of a report which compares the current state of the project and the expected state at the time of the next review. Such reports as shown can be used in progress review and look-ahead planning meetings.

Finally, a schedule that is represented through a bar-chart or a network diagram on site might be very difficult to interpret for most workers or engineers due to the large number of activities present and the complexity of the relationships and the notations. Alternative schedules can be created with the help of snapshots generated through the 4D model such as the one shown in Fig. 10, that affix visual information to daily or weekly milestones, thus making it easier for project participants to interpret schedule information and progress targets.

Such tools that can be developed on top of existing 4D tools have the potential to integrate the outputs of 4D simulations with existing project management tasks and processes, and to automate the generation of a series of reports that can be used as decision making aids by planners and managers to assess project progress, foresee bottlenecks and plan ahead. Such automated integration of 4D and project management might reduce barriers for the adoption of 4D technology. In particular, the applications mentioned in this section allow practitioners to use the outputs of 4D models in those areas where our quantitative analysis has indicated that 4D CAD can provide the greatest benefits—viz. visualizing projects and communicating information for the benefit of clients and workers, reviewing project progress and assessing constructability. It should however be noted that this discussion is presented more as a conceptual overview. Further research needs to be done in this direction to develop and validate a robust set of tools for implementation on construction projects.

This paper set out to assess the potential for using 4D CAD in construction by seeking to understand the conditions under which 4D

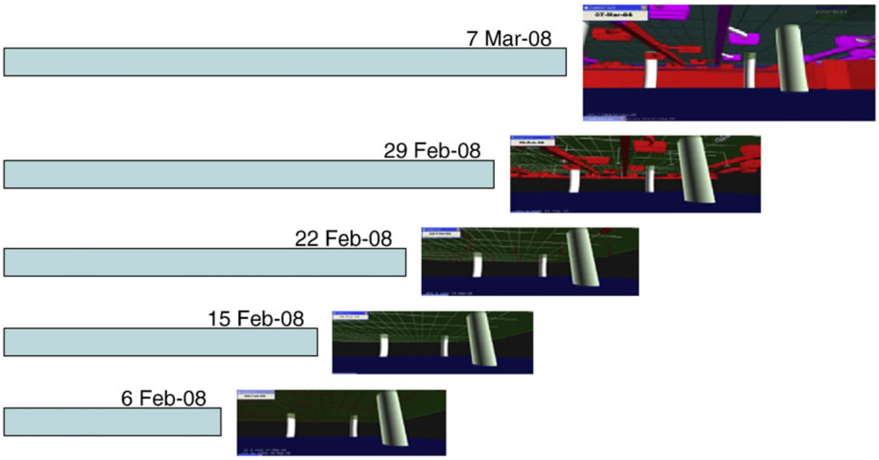

Fig. 10. Visualization of schedules.

CAD might yield useful insights and how 4D CAD can be used to derive benefits on construction projects. A combination of qualitative and quantitative analysis has helped provide inputs that begin to answer these questions. Decidedly there are limitations to the analysis undertaken. First, all our respondents as well as the projects we studied came from India. There is therefore the likelihood that our results might reflect a cultural bias. This can be verified by future work that replicates our study in other geographical theatres. However, as we have suggested earlier, we carefully chose project sites such that the project characteristics as well as the nature of the problems encountered are fairly representative and are not esoteric to the Indian context. Our experiences in interacting with project personnel and modelling projects bear this out, since the challenges faced, the processes followed as well as the insights we received seem fairly representative of the construction context in developing economies. We thus have reason to believe that our findings, while based on data from India, are relevant to and of broad interest to a wider audience. Second, the limited size of our sample of projects makes our results indicative rather than conclusive. A larger sample of projects across various other sectors such as residential, industrial construction and so on can be studied to confirm and generalize some of the insights developed in this paper.

Despite these limitations, this paper has sought to address a more fundamental question that might be of great relevance to practitioners and to the construction industry as a whole, and which has not thus far been systematically addressed either in practice or in academia. This question relates to whether, despite its theoretical benefits, 4D CAD can be effectively used and implemented to benefit the construction industry. The evidence presented here shows that it can, significantly.

Acknowledgements

This research was funded by Autodesk. The writers would also like to thank Larsen and Toubro ECC, Tata Consultancy Services and IIT-Madras for their participation in this research study.

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