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Moving beyond the fourth dimension with an IFC-based single project database

Ali Murat Tanyer[a,b,*], Ghassan Aouad[a]

[a] *School of Construction and Property Management, University of Salford, Salford, Greater Manchester, M7 1NU, United Kingdom*
[b] *Middle East Technical University, Faculty of Architecture, Department of Architecture, 06531, Ankara, Turkey*

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Abstract

4D CAD has been an active research area for many years. The first generation 4D tools simulated construction schedules and demonstrated the potential benefits in several case studies. Researchers tried to improve the functionality of the first generation 4D tools by adding annotations and highlighting the building elements that have problems. The future generation 4D tools are expected to include more than these. It has been envisioned that 4D models would be part of project databases in order to take decisions related with different project dimensions.

This paper presents the development and implementation of a new 4D planning tool which is a part of a product model-based project database. This tool brings the 4D simulation and cost estimation together and aims to contribute to what-if analysis in construction projects. The last part of the paper presents a case study in which the proposed prototype is evaluated.

Keywords: 4D CAD; Industry Foundation Classes (IFC); Implementation; Single project database; What-if analysis

1. Introduction

A construction project includes many parties from its inception through to its demolition. There is high interaction between these parties in terms of exchanging project information. Today, most of the information can be produced electronically by using special computer programs. However, parties included in a construction project usually share paper-based views of project information. These documents neither present the relationships between project deliverables nor highlight important and critical information [15]. To give an example, there is no visual connection between the design documents and the project schedules; construction planners visualise the relationships mentally and try to identify possible problems before construction stage. The mental visualisation of project information prevents project teams taking critical decisions easily and quickly. Four-dimensional

* Corresponding author. Tel.: +44-161-295-4815; fax: +44-161-295-5011.

E-mail addresses: A.M.Tanyer@pgr.salford.ac.uk (A.M. Tanyer), G.Aouad@salford.ac.uk (G. Aouad).

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CAD (4D CAD) has been recognised as a possible solution to provide the link between the design information and the project planning information.

Numerous research have been carried out related with the functionality, implication and applications of 4D CAD within the construction industry. Most of these research tools concentrated on two of the project dimensions: 3D design and scheduling. In spite of its well-documented advantages, 4D CAD is separated from other project information such as cost, maintenance, thermal and acoustical requirements, etc. Integrating 4D tools with 'single project databases' could help us create this missing link.

This paper presents a research prototype, which is a part of an IFC-based single project database. First, a literature review of the 4D CAD is given. Next, the benefits and limitations of current 4D products are presented. After that, a new 4D planning tool, which is a part of a project database, is introduced. The paper is finalised by the demonstration of a case study in which the proposed 4D tool was evaluated.

2. Background research in 4D CAD

Research in 4D CAD has mainly been driven by the lack of integration of project information, namely the design and the schedule information. Architects are now using CAD packages in order to produce the design of the project. On the other hand, planners use CPM-based networks and bar charts to describe the proposed schedule of a project [5]. These networks and charts help to coordinate the activities of construction projects. However, CPM schedules do not provide any information pertaining to the spatial context of the project [5]. Therefore, to identify spatial aspects of a project, users must look at 2D drawings and conceptually associate the components with related activities [5]. Within this process, project members spend a lot of time visualising the construction project while working on the project schedule. This mental model represents the associations between time (schedule) and space (the building model) [18]. 4D CAD removes this abstraction by representing the associations between schedule information and CAD information through a 4D movie that visually communicates the sequence of building construction [18].

For many years, several research have been conducted about 4D CAD. The following sections summarise the 4D CAD research under three main subsections: (i) First generation 4D tools, (ii) second generation 4D tools and (iii) next generation 4D tools. A short description of the benefits and limitations of the 4D CAD tools were also presented.

2.1. First generation 4D tools

Research in the 4D visualisation goes back to early 1990s. Retik [3] used VR techniques to present the simulation of a construction process. This system allows the user to visualise different stages of the construction project by a VR package. Later efforts include the development of the 4D models for the San Mateo Health Facility between 1993 and 1995 [1] and roof for Haas School of Business at 1995 [1] by the Center for Integrated Facility Engineering (CIFE) at Stanford University. Due to the success of the these projects, CIFE continued to pursue research related to 4D models, focusing on improving 4D tools and the value of 4D models in design and construction [7]. Songer et al. [2] and Koo and Fischer [5] have also developed construction process simulation tools or quantified the benefits of these tools with end users.

The first generation 4D CAD applications have only created the simulation of construction processes in a virtual reality (VR) environment. These tools are good to explain the rationale behind the schedule in a visual way. Liston et al. [16] stated that current 4D tools mainly facilitate explanative tasks.[1] This has been further depicted in the following figure, which compares the time spent to perform project tasks with and without 4D practices. This figure explains that, although 4D models support explanative tasks, they need to be enhanced in order to facilitate the predictive tasks, which are very important in a project life cycle (Fig. 1).

[1] Liston et al. [16] identified four types of tasks in a typical project meeting: Descriptive tasks: Describing the "who", "what", "where", "when", and "how" of the project. Explanative tasks: Explaining project decisions or the schedule rationale the "why" questions. Evaluative tasks: Evaluating project goals and checking that project requirements are met. Predictive tasks: Predicting impacts of changes or specific decisions on project goals asking "what if" and "what happens" to questions.

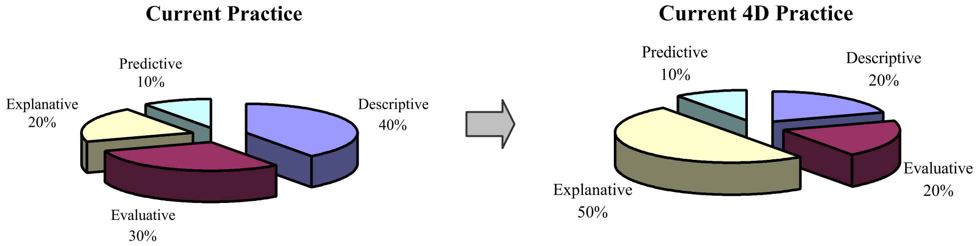

Fig. 1. Analysis of time spent performing tasks in current practice and current 4D practice (source: Ref. [16]).

2.2. Second generation 4D tools

The first generation 4D tools proved the benefits of combining the design information with the project schedule. These tools allow project members to determine potential problems in advance. However, it is also understood that 4D tools need to be more than visualising the project schedules. This would improve the contribution of the 4D models to the decision making process in a project meeting.

Researchers tried to increase the functionality of 4D models by applying different presentation techniques: For example, Liston et al. [13] proposed using *annotations* that visually explain potential constructability problems. The annotations inform the planner where and when the problem occurs. Another research by Liston et al. [14] compared two visualisation techniques—*highlighting* and *overlaying*. Liston et al. [14] defined *highlighting* as the process of emphasising, through visual annotation, related sets of information within a view and across multiple views and *overlaying* as the process of placing one set of information onto another set of information that results in one merged view. Liston et al.'s [14] hypothesis was that overlaying and highlighting techniques would reduce (i) the time spent performing *descriptive*, *evaluative* and *explanative tasks* and (ii) the influence of task complexity on task accuracy and task completion. The main aim of this study was to reveal how these two techniques would improve visualisation of information.

McKinney et al. [17] proposed an interactive 4D CAD tool in which planners could interactively generate CAD, schedule and 4D content. In this environment, the planner had access to all of the 4D content such as design, schedule and their relationships. The main aim of McKinney et al.'s [17] work was to improve the interaction between the scheduler and designer and to improve the process of creating a 4D animation.

Some work has recently been undertaken to improve space-planning functionality of 4D tools. Akinci et al. [4] discussed the potential of including workspaces as objects in the 4D simulations to determine potential space–time conflicts. Akinci et al. [4] proposed two prototype systems, namely *4D Workplanner Space Generator* and *4D Workplanner Time–Space Conflict Analyser*.

With the second-generation 4D tools, user can access to the improved visualisation information. However, predictions are still limited as there is no connection between the 4D simulation and other project dimensions such as cost, maintenance, thermal and acoustical simulations, etc.

2.3. Benefits of 4D CAD

4D models represent a fundamental change in project planning, design and construction management strategies of companies [6]. They not only maximise the utility of the 3D models but also promote interaction between project participants [5].

4D models help identifying and eliminating the construction related problems before going to site. Koo and Fischer [5] investigated whether 4D could help project participants identify problems that would normally be overlooked in traditional bar chart techniques. This work concluded that 4D models communicate a schedule more clearly and enable even relatively inexperienced construction professionals to identify problems. The identification of problems before materialising could help companies save time and money in the long term. Goldstein [9] stated that firms could save a substantial amount of time/money by fixing schedule conflicts in virtual space before they materialise in the real world. Goldstein [9] quoted that 20–45% of change costs could have been prevented through 4D models and the potential savings of 4D tools could be in the range of 4–6% of overall project costs. 4D models also provide basis for analysing time–space conflicts, safety issues and site workspace management.

2.4. Shortcomings of the previous 4D tools

In spite of the stated benefits, some shortcomings also appear and because of these shortcomings, current 4D tools have not been taken up by the industry to a large extent. Major shortcomings of today's 4D tools can be summarised as below.

2.4.1. Creation of 4D models is time consuming

Before creating 4D simulations, 3D models of the construction projects should be produced. If a 3D model is not present, it takes a lot of time to convert 2D drawings to 3D models. 4D simulations, which are created by linking the 3D design and the time information manually, would require a lot of time. As a result of this, 4D has remained a tool that is implemented in large and complex projects. While a number of large companies are investigating the potential of 4D in pilot projects, sceptics believe that 4D is still too labour intensive and too complicated to be widely adopted by the AEC sector [9].

2.4.2. Manipulation of 4D models is time consuming

Producing different 4D simulations for different conditions is a difficult task with today's 4D tools. A new 4D model needs to be built for every new situation or for different levels of detail. For any change in either building geometry or activity constraints, time consuming updates have to be made to amend the associated links. Because of this problem, project teams do not have much chance to view alternative simulations for different conditions.

2.4.3. Visualisation should include more than just the graphic representation of the building

Construction planners viewing 4D animations want to see equipment, scaffolding, staging and work areas, etc. [18]. These elements are just as important to the planner as the building elements. Furthermore, planners want to see other process information such as interferences and congestions [18]. A 4D simulation must not only present the visualisation of construction processes but must also present possible problem areas in the model, e.g. by blinking colour. Researchers began to address these problems in several research prototypes (for example, see Ref. [13]).

2.4.4. 4D does not support the construction knowledge

When producing the 3D model, each building element, such as wall, slab, column, etc., is generally drawn as single entities. However, at a construction site, building elements may be built in phases depending on the site conditions and experiences of the site professionals (e.g. pouring a large concrete slab in phases). This kind of knowledge should be reflected into the production of the 4D models.

2.4.5. 4D is not integrated with other project data

Current 4D tools are designed to visualise project schedules. However, a construction project includes dimensions other than 3D and time. The missing link between 4D CAD and other project information prevents us to take real benefits from the construction simulation. Barrett [23] elaborated this issue by stating that 4D CAD systems need to be a part of wide range project models. Current 'nD CAD' project at the Salford University is an example to this kind of system. nD CAD tools include different dimensions of a construction project such as cost, environmental, maintenance-related data (see Ref. [22] for more information about the nD CAD project).

3. Discussion

Current research in 4D CAD has addressed some of the above listed problems. For example, researchers are trying to improve the 4D models by adding equipments (such as scaffoldings, cranes, etc.), including staging and work areas, and highlighting the problem areas in the 4D visualisation. There are also previous research efforts that have considered 4D simulation as a part of integrated environments (see Section 3.1). Such additions have improved the 4D models significantly. In spite of these improvements, 4D tools are still limited in contributing to the predictive tasks in construction projects. Liston et al. [16] have elaborated this with the following figure (see Fig. 2). One main reason of this is the separation of the project dimensions from the 4D simulation.

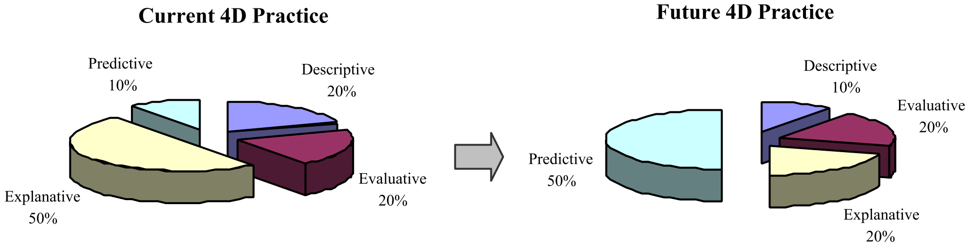

Fig. 2. Analysis of time spent performing tasks in current 4D practice and future goal (source: Ref. [16]).

Future 4D models are required to contribute to the predictive tasks related to the project decisions. Checking different dimensions of a construction project together with the 4D data is an ultimate target of researchers. This vision is examined in the following section, which summarises the *next-generation 4D tools*.

3.1. Next generation 4D tools

The previous section has stated that future 4D models are expected to: (i) effectively communicate the project data, (ii) rapidly explore project execution alternatives and (iii) integrated with other project information. One way to satisfy these requirements is considering 4D models as a part of 'integrated computer environments'. Computer-integrated construction has long been in the agenda of researchers and many research projects have been designed in order to improve the data sharing problems between construction parties. For example, Faraj and Alshawi [10] and Aouad et al. [8] have proposed 4D tools, which are part of integrated project databases. Although these research projects have initiated the idea of integrating 4D models to project databases, one big problem is the dependency to a third party software application.

Currently, IFC provide a neutral data exchange mechanism for the construction related data. IFC specify the 'things' that are used in building construction in an agreed manner and they define a common language for construction. IFC are developed by the International Alliance for Interoperability (IAI) to provide a foundation for the exchange and sharing of information directly between software applications and define a shared building project model [12].

There are two ways of data exchange with IFC (see Fig. 3):

- Exchanging the IFC data using a physical medium such as floppy disk or email;
- Sharing the IFC data via a central project database.

Within the last couple of years exchanging the IFC data via a physical medium has been tried in a couple of projects. For example, European Community (EU)

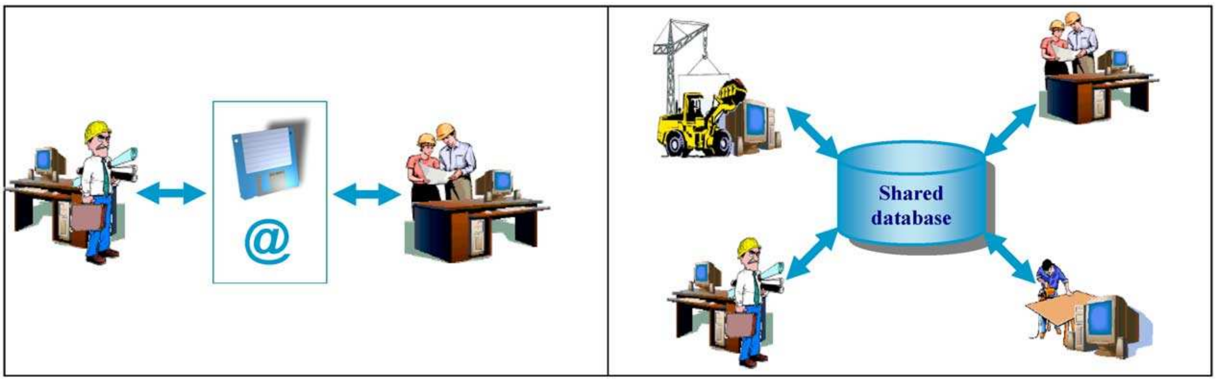

Fig. 3. Two ways of data exchange using the IFC.

supported Information Society Technology (IST) project called DIVERCITY (Distributed Virtual Workspace for Enhancing Communication within the Construction Industry) [21] is an example to this kind of data exchange. In this project, researchers developed IFC compatible prototypes and experimented with them in terms of 4D, acoustical, thermal simulations. Fischer and Kam [20] have also carried out a pilot case study, which corresponds to the first approach. They have tested out the opportunities and challenges of the product model data sharing in different applications such as 4D, thermal, lighting simulations.

In similar research projects, the IFC file has to be transferred between the project parties in order to analyse different dimensions of the construction projects. This approach allows little opportunity for the project partners to make multicriteria decision-making considering different project dimensions at the same time.

Integrating different project dimensions by the help of project databases could allow us to make multi-criteria decision-making (Fischer and Liston [19] and nD Modelling [22]). Fischer and Liston [19] envision that future 4D tools will be part of project databases, which will store and maintain the representation of building components and construction activities, their inter-relationships and relationships to other project data. This project database will not only support the 4D content but also other project information such as design, cost, workspaces, thermal and acoustical information, etc. Fischer and Liston [19] detail their vision by stating that 4D technologies will be used to analyse and visualise many aspects of a construction project, from the 3D design of a project to the sequence of construction to the relationships between schedule, cost and resource availability data. 4D technologies will no longer be used to simply animate the sequence of construction but will be used to communicate a wide range of project data much more clearly and efficiently than possible today.

The above discussion has encouraged the researcher to develop a new 4D planning tool which is a part of an IFC compatible shared project database. The following section presents this 4D prototype. The new 4D prototype allows project participants to examine different dimensions of a project (design, time and cost) within the same user interface. It can therefore be used to make multi-criteria decision-making considering the stated dimensions.

4. Proposed system

The proposed system is a web-based 4D planning tool. All project information is kept at a central project database and parties can access to the information through the database as and when they want. The database keeps and manages the information as objects, which are created directly from the IFC model. The following section explains the information flow within the system and the architecture of the system, respectively.

4.1. Information flow within the system

Before the development phase, the information flow within the system was modelled in order to have a general idea of the system. The modelling was done using the IDEFØ technique to understand what information types are needed in which stages within the whole process. IDEFØ is a structured technique that combines graphical language with text-based descriptions. Each process in a system is represented with a rectangular box and the relationships of the boxes are shown by arrows. The arrows can go from outside to inside or vice versa. Basically: (i) the arrows entering to a box from the left side are the *inputs* of a process; (ii) the arrows leaving a box from the right side are the *outputs* of a process; (iii) the arrows entering a box from the top side are the *control* of a process; (iv) the arrows entering a box from the bottom side are the *mechanisms* of a process (Fig. 4).

Four main processes were identified within the system. These are: (i) prepare 3D model, (ii) prepare project plan, (iii) prepare 4D simulation and (iv) prepare cost estimation. Except the first one, all other processes can be carried out using the proposed prototype. The prototype expects the 3D model of the building produced in an IFC certified CAD package.

4.2. Architecture of the system

The system is based on a three-tier architecture. Within the three-tier architecture, each facet of the

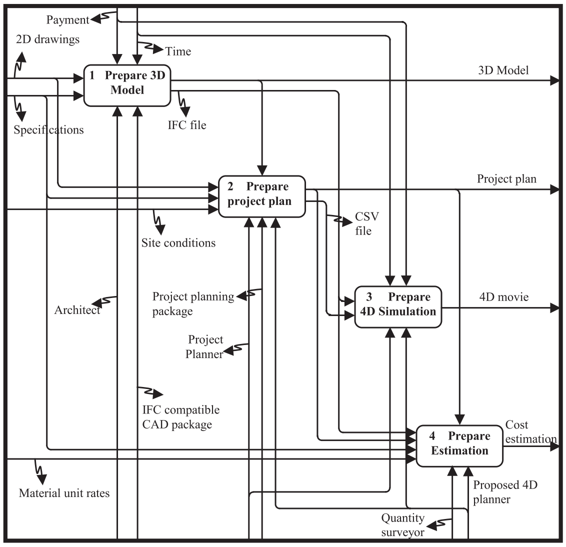

Fig. 4. Information flow within the system using the IDEFØ technique.

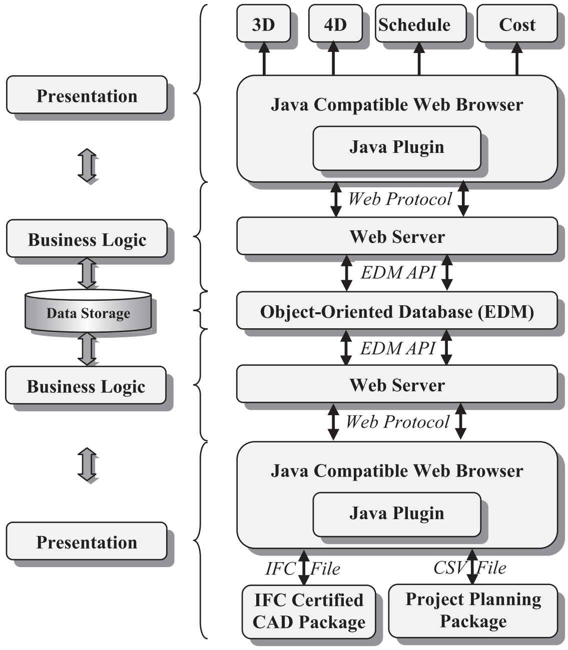

Fig. 5. Architecture of the proposed system.

application, i.e. presentation (user interface), logic (processing) and data storage (database), is isolated providing benefits such as maximum control, scalability and flexibility [11]. Designing the application in layers, or tiers, is useful for many different reasons. In a multiple tier design, each tier can be run on a separate machine, or machines in different locations, allowing for improved processing performance. The architecture of the system is shown in Fig. 5.

The following section explains the architecture of the system in detail considering the three layers stated.

4.2.1. Data storage layer

At the *lowest level* of the system architecture, the main project database was implemented. An object-oriented database, called 'EXPRESS Data Manager (EDM), was used as it supports all EXPRESS statements, expressions, built-in functions, procedures, EXPRESS-driven data exchange file specification (Part 21) and Standard Data Access Interface (SDAI).

The database can store and manage different EXPRESS schemas. The version 1.5.1 of the IFC was selected, as it was the common data model to which all major CAD packages complied when this research started. Currently, main CAD vendors are planning to move to IFC version 2×2, which provides a more robust data exchange mechanism according to the IAI.

4.2.2. Business logic layer

This *middle layer* provides process management where business logic and rules are executed. This is where the code of the system regarding the data is stored and is the bulk of the application. This layer creates the graphical user interface (GUI), establishes the link between the GUI and the database, queries the database and manages the data in order to create the 4D simulation and the cost estimation.

There are six main processes that are managed with the business logic layer.

4.2.2.1. Define a project database. The database is designed to store and process all information defined in EXPRESS and EXPRESS-X schemas (dictionary data) and populations thereof (application data). *Data* are stored as instances in a *model*. A model is a logical container for entity instances defined by one EXPRESS schema. Data models are available with the specified name in the specified repository.

To start working with the prototype, the user either creates a new project database or opens an existing project database via the GUI. The user then gives a unique name to the database and a password to control the access rights to the data. The database needs to be populated with an IFC file. All the instances in the IFC file are stored as new instances that are compatible to the database.

4.2.2.2. Query database to visualise the IFC file. The project database is first queried for the building storeys in order to find out the relating building element instances. Data related with the building storeys are kept within the 'IFCBuildingStorey' instances. The '*contains*' attribute of this class gives the relationships of the IFCBuildingStorey instances with the IFCBuildingElement instances (see Fig. 6). By the help of this attribute, it is possible to understand which IFCBuildingElements are related to which IFCBuildingStorey. Seven types of IFC-BuildingElements—namely IFCBeam, IFCColumn, IFCDoor, IFCFloor, IFCRoofslab, IFCWall, IFC-Window—are searched for each building storey.

4.2.2.3. Create each building element on screen. As soon as an IFCBuildingElement instance (e.g. IFC-Wall) is found in one of the building storeys, a new query starts in order to capture the necessary information to create that element in the visualisation screen. The data needed in this second query are the geometry and the locations of the building objects. The information related to these items are stored in the instances of the IFCProductShape and IFCLocal-Placement (see Fig. 7).

Once a building element instance, such as IFC-Wall, is queried and the required information (e.g. geometry, location, etc.) are captured, the building element is created on the screen using Java 3D. Java 3D is a powerful 3D modelling tool, especially for portable applications. All the complex mathematical transformations are carried out automatically with Java 3D. This has provided a real advantage in the production of the scene.

4.2.2.4. Create construction planning. When the creation of the building elements in the GUI is complete, the user can start building the project plan of the construction. The project plan can be created from scratch using the GUI of the prototype or it can be imported to the system from the well-known off-the-shelf project planning packages, such as MS Project. If the second option is selected, the project plan should be prepared in a third party project planning package and then should be exported to Comma Separated Value (CSV) file format. CSV is a text-based file format and it is used to make the third party project planning packages and the prototype communicate. The main reason for using CSV as a medium to communicate with the database was the lack of IFC compatible project planning packages. As a result of this, a translator between the CSV files and IFC object model was

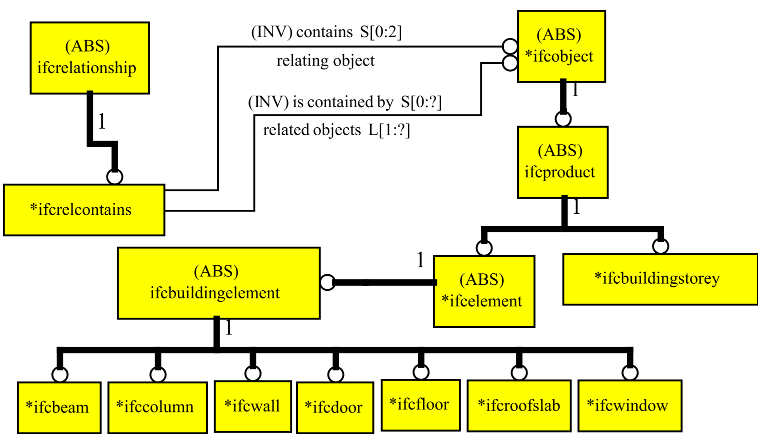

Fig. 6. EXPRESS-G representation of the relationship between IFCBuildingElements and IFCBuildingStorey.

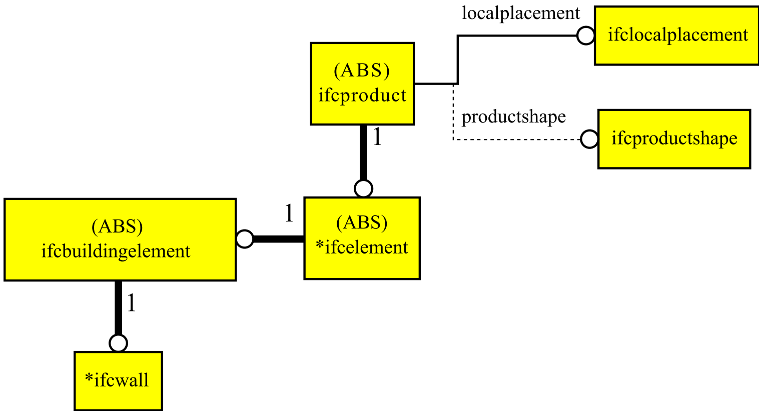

Fig. 7. EXPRESS-G representation of the IFCProductShape and IFCLocalPlacement classes.

written. This translator converts the planning information to IFC classes.

4.2.2.5. Update the database. Before the linking process, the database has to be populated with the time information that was entered to the Gantt Chart. The update of the database creates instances of IFCWorkTask and IFCWorkSchedule in the database (and in the IFC model as well). These two classes are the extensions of IFCProcess class and hold the information related to project processes. Fig. 8 presents the EXPRESS-G representation of the *IFCWorkTask* and *IFCWorkSchedule* classes.

4.2.2.6. Link building elements to time information. The building elements have to be linked to the related worktasks to see the 4D simulation. To do this, the user selects the elements from the visualisation screen or from the tree structure via mouse clicks (see the GUI in Fig. 10). The selected elements are highlighted with green colour. Once all the building elements, related to a worktask, are highlighted, the worktask has to be selected via the mouse as well. The selected building elements and the worktask are linked as soon as the user presses the *link* button. The user can unlink the elements at any stage of the linking process by selecting the element and pressing the *unlink* button.

The relationships of the building elements and worktasks are kept within the *IfcRelProcessesProducts* instances. For each link, an instance of *IfcRelProcessesProducts* is created. Next, the attributes, namely *RelatedProducts* and *RelatedProcess*, of each instance are populated with the instances of the building elements and worktasks. Figure 9 presents the EXPRESS-G representation of the *IFCProduct*, *IFCWorkTask* and *IFCRelProcesses-Products* classes.

4.2.2.7. View simulation. Viewing the simulation is done by querying the *IfcRelProcessesProducts* instances, which keeps the relationship of the building elements with the time information. By the help of the attributes of the *IfcRelProcesses-Products*, namely *RelatedProducts* and *RelatingProcess*, we can understand which building elements are related to which worktask. The attribute *RelatedProducts* provides the references to products that are either inputs or outputs to the process. This attribute gives a list of IFCProduct (IFCBuildingElements) instances. On the other hand, the attribute *RelatingProcess* provides the references to the process that handles the products as input or output. This attribute provides a connection to an IFCProcess (IFCWorkTask) instance.

When the query accesses to the *IFCWorkTask* instance via the *RelatingProcess* attribute, it checks the *actual start* attribute of the instance. This helps to identify the delay time of the worktask according to the project start date. Using this delay time, a Java3D behaviour object is attached to the related Java3D objects to control the appearance sequence and transparency on the screen during the 4D visualisation.

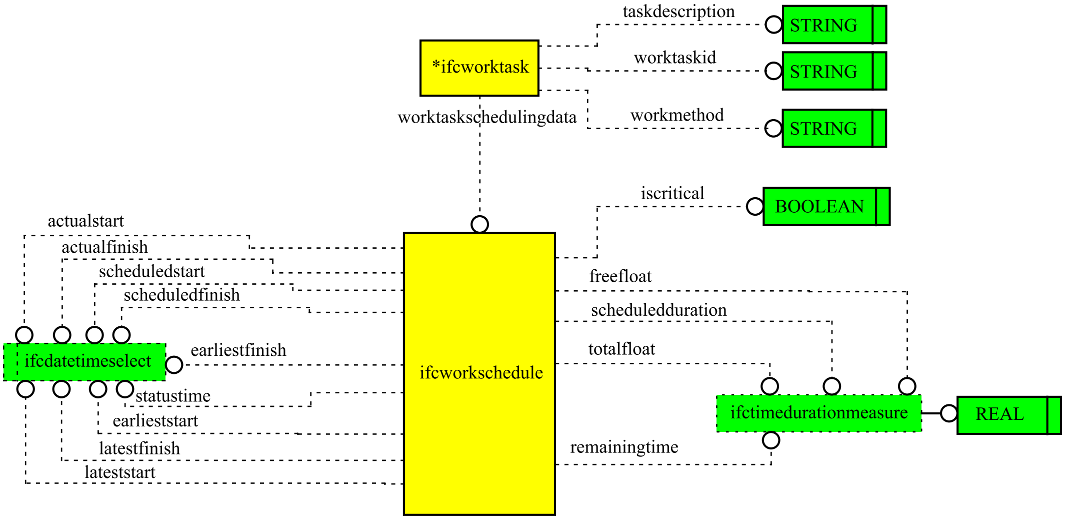

Fig. 8. EXPRESS-G representation of IFCWorkTask and IFCWorkSchedule classes in IFC.

4.2.2.8. Create cost estimation. The user uses the cost tab of the GUI to make a preliminary cost estimation of the construction project. The cost tab includes a cost estimation table, which is similar to an Excel sheet. The table has five columns with the following headers (see Table 1): (i) IFCObjects/IFCProcesses, (ii) quantity, (iii) unit, (iv) unit cost and (v) total cost.

The table is first populated with the data when the user submits an IFC design file to the database. The building elements in the IFC model are separated according to their types and dimensions. These data are then written to the table. To find out the cost of the building elements, the user has to enter a unit cost for each item in the table. The cost of the building element

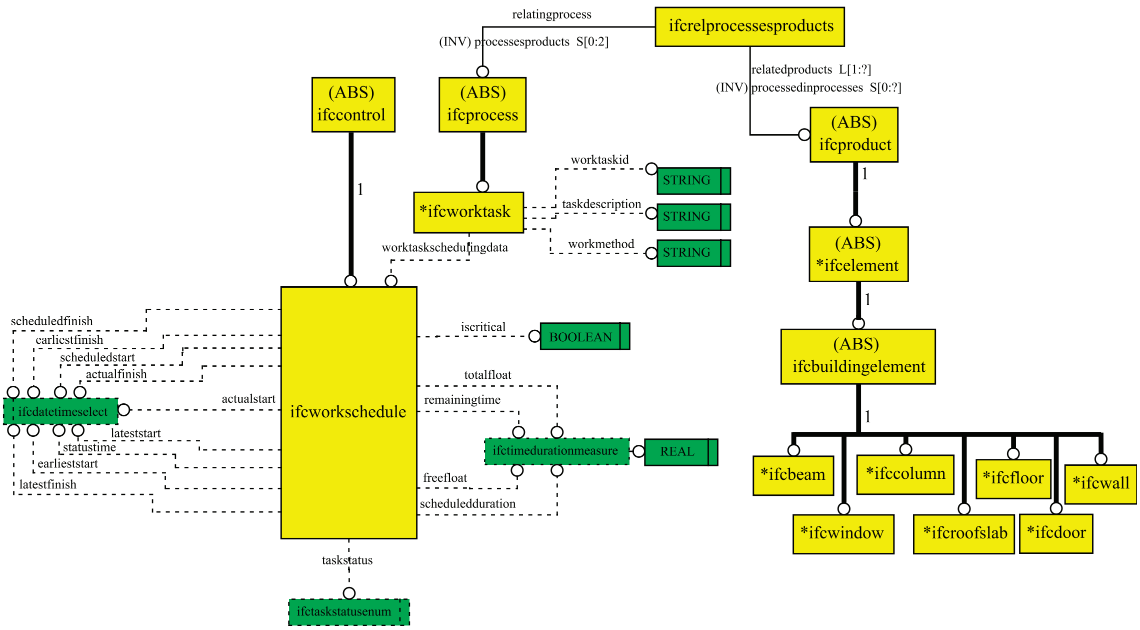

Fig. 9. EXPRESS-G representation the relationship between IfcProduct, IfcProcess and IfcRelProcessesProducts.

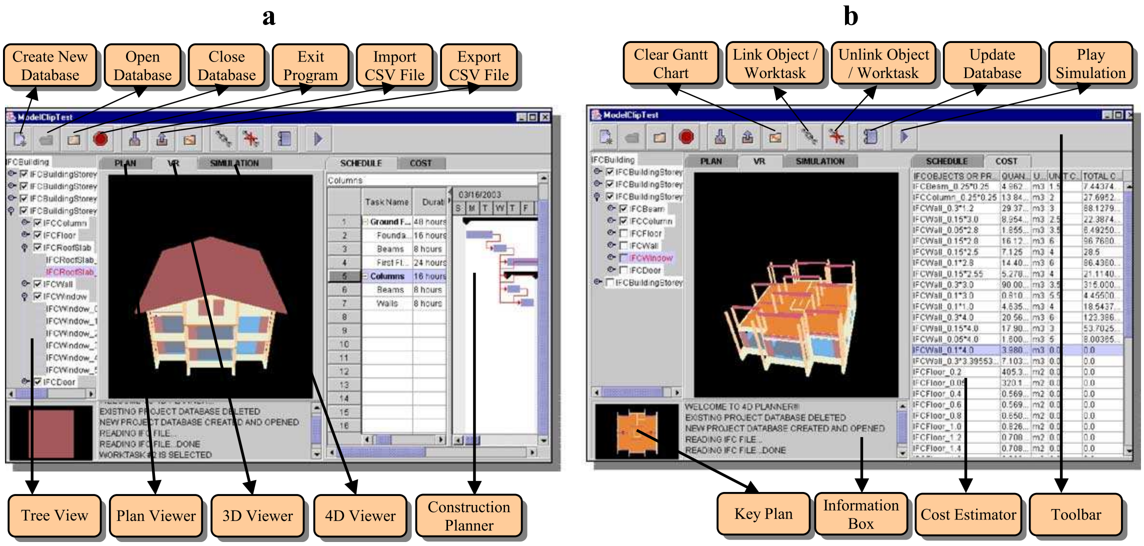

Fig. 10. Graphical user interface of the prototype. (a) GUI showing the scheduler, (b) GUI showing the estimator.

is calculated by multiplying the quantity and the unit cost of the element. The total cost is automatically calculated by adding the cost on each row.

4.2.3. Presentation layer

Finally, the *top level* provides the GUI of the overall system. The user interface appears within a web page and enables the user to interact with the system. Any JAVA compatible web browser is suitable for the program to run. The GUI has seven important parts (see GUI in Fig. 10):

- *Toolbar*: Basic operations, such as create/open project databases, load IFC files, import/export schedule information, etc. are controlled from this toolbar.
- *Tree structure which contains building elements*: The GUI contains a tree structure, which classifies all building elements according to building storeys and their types. The users can interact with the 3D model through this tree structure. Each building element can be highlighted by selecting from this tree view. There is also a function to control the visibility of building elements according to storeys or element groups.
- *Key plan*: A small key plan of the building model is presented in the GUI in order to provide a quick view of the building model when the user is dealing with the 3D or the 4D view.
- *Visualisation screen*: The plan, the 3D model and the 4D simulation of the construction is shown in this screen. The user can interact with the building elements via this interface.
- *Information box*: The user is informed about the processing via this information box (e.g. whether the database is created or the elements are linked to the selected worktask/s).
- *Construction planner*: This is a multi-feature Java Bean component that consists of grid and graph for managing project tasks. The component also has functions dealing with the basic file operations

Table 1
Cost estimation using the proposed prototype

IFC objects/processes	Quantity	Unit	Unit cost	Total cost
IFCBeam_0.25*0.40	4.96	m^3	.	.
IFCColumn_0.25*0.25	13.84	m^3	.	.
IFCWall_0.3*1.2	29.37	m^3	.	.
IFCSlab_0.2	405.3	m^2	.	.
IFCWindow_0.6*0.6	20	nu	.	.
IFCDoor_0.9*2.1	15	nu	.	.
Construct basement columns	3	day	.	.
Construct basement walls	5	day	.	.

such as open, print, close, etc. Users can add, edit or delete tasks as desired.
Schedule information can be produced by giving task names, durations, start/finish dates, etc. within the prototype. It is also possible to import project plans that are prepared with well-known off-the-shelf packages to the system.

- *Cost estimator*: There is a basic cost estimator within the system. When the user submits an IFC file to the database, the main building elements are separated according to their type (e.g. wall, beam, column, window, etc.) and dimensions. The table is updated with the elements and their quantities. The total material cost is calculated after the user fills in the unit costs of the building elements.

It is also possible to find out the costs of processes: When the project plan is ready, the user updates the database with the worktask information and this information is also written to the cost estimation table. The user again fills in the unit costs of the different processes and finds out the total cost of the construction, including the material and process costs.

5. Validation of the proposed tool

The proposed tool was validated first with an offline test case, which only included the researcher and then with an online test case, which included parties from an ongoing construction project at the time of the implementation. The online testing included project parties such as project planner (PP) and the quantity surveyor (QS). The PP was responsible from the production of the project plan and the QS was responsible from the cost estimation of the project. The two level testing strategy has validated the proposed prototype from the researchers' and end users' point of view. These test cases are illustrated in Fig. 11:

5.1. Scenario of using the system

The system necessitates several parties working together. The project parties are all connected with a common project website that includes the GUI of the prototype. The project manager can monitor and control the relationships between different parties.

The architect first has to produce the 3D object model of the construction project with an IFC certified CAD package. He then has to export the model to an IFC file. After that, the architect should log on to the project website and populate the database with the IFC file. The IFC file is sent to the database, which is installed on a central project server. The system reads the geometrical data that is stored in the database and processes this data to produce the 3D model within the GUI. Different users can access to the 3D VR model of the construction project via their web browsers.

At the next step, the PP produces the project plan of the construction by using the proposed IT prototype. Alternatively, the user can import a project plan,

a b

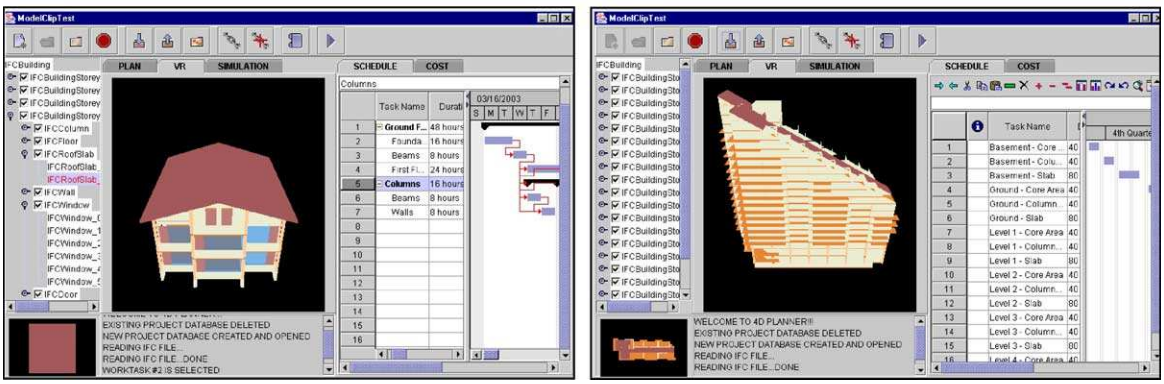

Fig. 11. Offline and online test cases with the proposed 4D tool. (a) Offline test case, (b) online test case.

which was produced with well-known commercial off the shelf project planning packages (e.g. MS Project), to the system. If the second option is selected, the project plan should be exported to a CSV file format in order to be imported into the system.

Once the project plan is ready, the planner updates the database with the schedule information. The planner then starts linking the building elements to the associated schedule elements. The 4D simulation can be viewed at any stage of the linking process. The simulation can also be shared between project parties via email or file downloading since it is also recorded as a separate file that can be viewed with many media player programs on computers.

If project parties recognise problem areas within the simulation, possible updates, such as changes in the duration of the tasks or adding/deleting schedule tasks, should be made via the GUI. The changes are reflected to the simulation as soon as the database is updated with the new information.

Finally, the QS prepares the cost estimation of the project via the GUI of the prototype. The quantities needed for the estimation are calculated automatically as soon as the architect populates the database with the IFC version of the project design.

Fig. 12 presents the above scenario graphically.

This proposed scenario brings the following advantages to the project parties:

- Parties can access to the project data which is centrally located from any location using a standard web browser that supports Java Runtime Environment (JRE) and Java 3D Runtime for JRE.
- The IFC approach provides a neutral data exchange between software applications.
- Project partners can carry out 'what-if analysis' considering the different dimensions of the project (currently time and cost). This facilitates the problem area that was introduced in Section 2.4.5 (4D is not integrated with other project data).

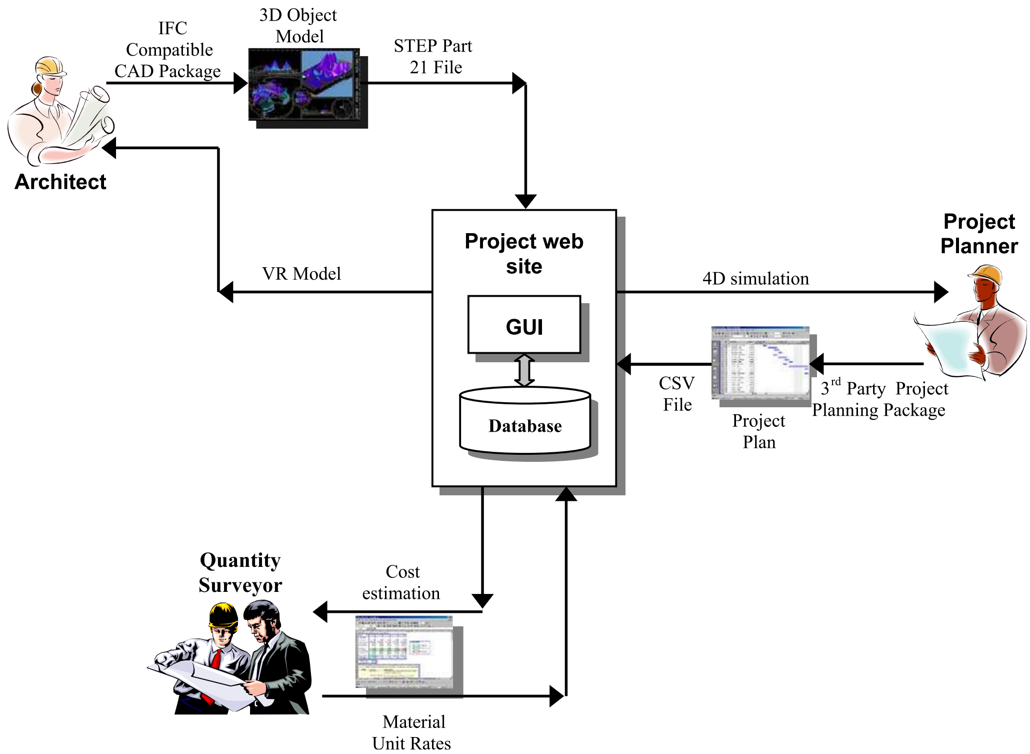

Fig. 12. User scenario.

- Alternative simulations could be created without much work as the linkages are kept within the database. This facilitates the problem areas that were introduced in Sections 2.4.1 and 2.4.2 (creation and manipulation of 4D models are time consuming tasks).

5.2. User testing of the system

The above scenario was tested with the related project parties (the project planner and the quantity surveyor) in an ongoing construction project. The selected construction project is a housing complex and it is situated at a riverside location at the heart of Manchester. The project consists of four blocks all of which are made up of reinforced concrete frame (Fig. 13).

To carry out the case study, the architectural drawings were obtained from the contractor. All of these drawings were in 2D format so the researcher had to produce the 3D object model of the architectural design from these drawings with an IFC certified CAD package. After the 3D model was produced, an IFC 1.5.1 file was produced from the 3D model with an IFC certified CAD package. The project parties have not been involved in the production of the 3D model because of their workloads.

The second part of the case study includes the production of the project schedule. The original project plan was prepared by the construction planner in a third party planning tool. This plan was obtained and was later exported to the CSV file format so that it could be imported to the proposed prototype.

5.2.1. Project planner's perspective

The project planner had created two alternatives related with the project plan: The first alternative was the construction of the curtain wall just after the concrete framework was finished (Fig. 14) and the second alternative was the construction of the curtain wall together with the concrete framework (Fig. 15). By using the GUI of the prototype, the project planner:

- created a new project database,
- submitted the design file which is in the IFC file format to the database,
- imported the project plan to the GUI of the prototype,
- updated the database with the time information,
- linked the design and time elements,
- created a 4D simulation corresponding to the project plan.

After viewing the first alternative, necessary updates related to the project plan (e.g. changing start/finish dates) were done in order to create the second alternative. The database was updated with the new project information and a new 4D simulation was created. Since the geometry, the time and the relationship information between these two were

a b

Fig. 13. The online case study. (a) 3D view, (b) project under construction.

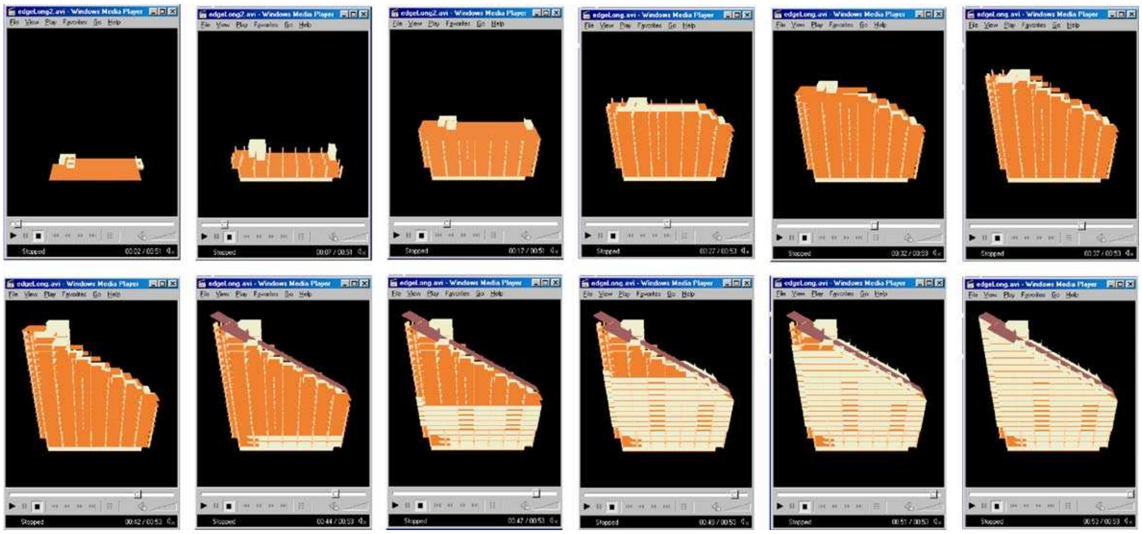

Fig. 14. First simulation alternative.

kept within the database, the creation of the second alternative took a shorter time compared with the first one.

Previously, the PP had chosen the first alternative for the construction project. With the two simulations, the PP compared the alternative construction sequences and identified the advantages/disadvantages of each case visually. The main disadvantage of the second alternative was that the curtain wall could be affected from the construction of the reinforced concrete frame.

5.2.2. *Quantity surveyor's perspective*

In order to make a preliminary cost estimation, the QS had to fill in the unit costs into the table (see Table 1), which appeared in the GUI of the prototype. For the previous two alternatives created by the PP, the QS had the chance to create two

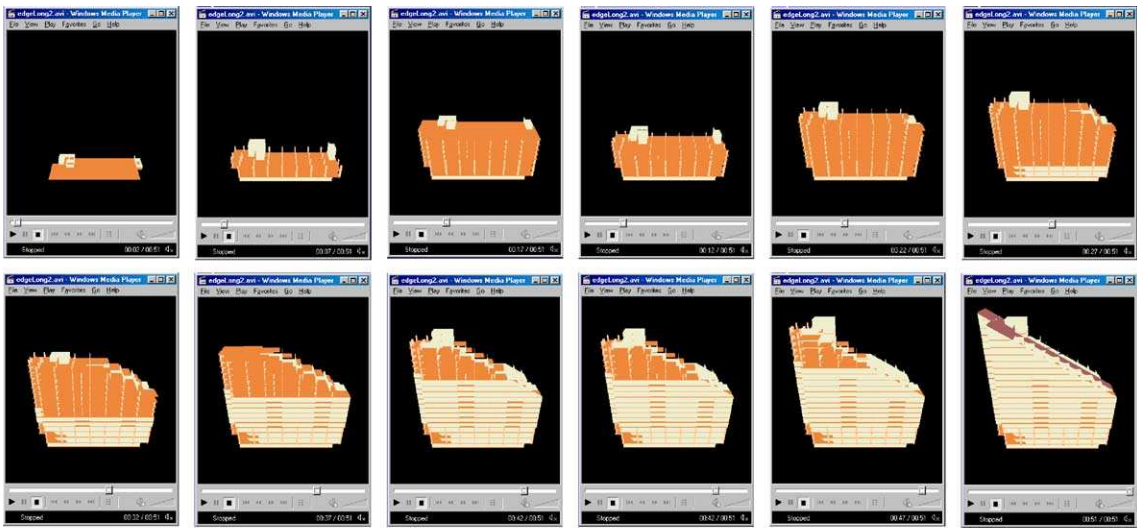

Fig. 15. Second simulation alternative.

different versions of the cost estimation. However, the QS questioned the suitability of the prototype to his current processes. The QS stated that the prototype was not appropriate to make a detailed cost estimation. To give an example, the QS stated that he needed six more items in order to make a detailed cost estimation of a single slab object. These extra items were: (i) formwork to support slab, (ii) edge formwork to support slab, (iii) reinforcement, (iv) concrete, (v) expansion joints and (vi) weather bar. The tool could automate the calculation of some of these items (e.g. area/volume of the slab). However, more work needs to be done in order to automate the others. With these conditions the tool appeared not to be suitable for a detailed cost estimation; however, it could well be used for a preliminary cost analysis at the tendering phase.

5.2.3. General discussion

The case study concentrated in improving the contribution of the 4D tools to predictive tasks in project decisions by the help of project databases. The database dependent 4D tool helped us to answer the 'what-if' and 'what happens to' questions in terms of schedule and cost estimation. Two alternative schedules were created and the relationship of the 4D simulation with the cost estimation was examined.

The case study has presented the capability of the prototype to produce different alternatives of project information for different conditions. This increases the contribution of 4D models to 'what-if' questions. The PP created two scenarios for the construction processes. For each scenario, the QS attempted to create cost estimations. However, he could not complete this since he found that the software was not suitable for detailed cost estimation. The benefit that the QS saw was the ability to make a preliminary cost estimation for the tendering phase.

The case study has also revealed the challenges of implementing the 'single database model'. The following section explains these challenges in detail.

6. Challenges of single project database

Although the proposed 4D prototype increased the number of alternatives and the relationship of the 4D models with other project dimensions (e.g. cost), the single project approach created some new problems. This section summarises these issues:

6.1. Traditional work practices

The construction industry has witnessed the elimination of the 'master architect' as projects become more and more complex. As a result of this, several expertise areas and professions have emerged. Today there are several parties that are responsible for the different sections of a construction project. The sharing of data between these parties is like a 'waterfall model'. A construction party finishes a job and passes the information to the next related party. This has created isolated 'process islands' for the project participants. Alshawi and Faraj (2002) stated that stage controlled processes within the industry have prevented many significant improvements from being applied to the industry.

In the case study, traditional work practices were a major problem as each party has concentrated solely into his/her own practices without thinking of the implications to the other party. To give an example, the project planner's main interest was not the cost dimension and the cost estimator's main interest was not the project planning. Although the proposed prototype tried to bring these together, the fragmentation within the industry prevented to take real benefits from the proposed 4D tool.

6.2. Level of detail in project deliverables

The level of detail in project deliverables was a big problem in a single database environment.

- *3D model was not very detailed*: On one hand, the IFC-based object model was not very detailed. For example, site knowledge (e.g. how the elements are going to be constructed—in phases or as single entities) and some objects (e.g. balcony steelwork) were not included in the 3D model. As a result of this lack of detail, conflicts appeared between the design file and the project schedule. For example, the PP could not find the equivalent of some worktasks in the 3D model.
- *3D model was very detailed*: On the other hand, the 3D file was very detailed for the project planner. The project planner was not interested in

every object in the model. For example in the case study there were no worktasks corresponding to the installation of doors in the project schedule. However, door objects were modelled in the 3D model.

Before starting the 4D modelling, the abstraction level of the 3D design file has to be decided by the project parties together to prevent similar conflicts.

6.3. The quality of the IFC file

There were problems in CAD to IFC conversion. During the testing with various IFC files, it was realised that not all of the certified CAD packages produced the correct IFC v1.5.1 data. A more detailed study about the problems of CAD-IFC conversion is available in the PM4D Report [20].

6.4. Size of the IFC file

Fischer and Kam [20] have indicated that the IFC representation files were up to five times the size of the original. A similar observation was done during the case study. The size of the IFC file was about double of the original file. Hence, the performance of the system was affected negatively. This problem was amplified when we populated the database (and the IFC file) with extra information such as worktasks (see Section 6.6).

6.5. Lack of 3D modelling

The 3D object model of the case project was not available. Hence, the researcher had to create the 3D model from the available 2D drawings. This process required long working hours. In real life conditions, architects should be compensated for the production of the 3D models. In order to take benefits from 4D or integrated project databases, the industry should first move from 2D to 3D modelling.

6.6. Management of the data in single project database

In an integrated database, the coordination and management of data and information is an important issue to be solved. Technologically, data access rights (who should access certain data at what stage of the project), data change rights (who can change the data and who should be notified) and database transactions (what happens when more than one person works on the same set of data) should be tackled. There should be a responsible party for assigning those relationships within the project life cycle.

Storing all information at a single medium also brings difficulties in the management of the data. When one starts mapping out different dimensions of project information, it becomes clear that a single data model would have to encompass enormous amount of information [24]. This increases the amount of objects that has to be modelled, so the performance of the software environment is affected.

7. Summary and further research

This paper has presented a new 4D planning tool which aimed at improving the contribution of 4D CAD to project decisions by integrating them with other project information. A new 4D prototype, which integrates design, schedule and cost dimensions, has been presented and a case study has been carried out in order to validate the tool.

The single database approach provided the opportunity to improve the ‘what-if’ questions as project parties could check different dimensions at the same time. Although this is a great advantage for the project participants, the case study has revealed that the single database approach has its own challenges during the implementation.

Further research needs to be done to scale-up the prototype developed so that it could be used in practice. Another recommendation of this paper is evaluating the prototype effort in different conditions in order to reveal the end user, organisation and business implications (opportunities/challenges) of integration.

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