A contextual AR model based system on-site construction planning

Item Type	Thesis or dissertation
Authors	Moore, Nigel Jonathan
Publisher	University of Wolverhampton
Download date	
Link to Item	http://hdl.handle.net/2436/301614

A MODEL BASED SYSTEM FOR CONTEXTUAL ON-SITE CONSTRUCTION PLANNING IN AUGMNENTED REALITY

NIGEL MOORE

Ph.D. 2013

A MODEL BASED SYSTEM FOR CONTEXTUAL ON-SITE CONSTRUCTION PLANNING IN AUGMENTED REALITY

NIGEL MOORE BSc (Hons)

A thesis submitted in partial fulfilment of the requirements of
University of Wolverhampton for the degree of
Doctor of Philosophy

This research was carried out with
the support of the
University of Wolverhampton

April 2013

This work or any part thereof has not previously been presented in any form to the University or to any other body whether for the purposes of assessment, publication or for any other purpose. Save for any express acknowledgements, references and or bibliographies cited in this work. I confirm that the intellectual content of the work is the result of my own efforts and no other person.

Signed ………………………………………………..

Date…………………………………………………..

To my wonderful Jess and my children Jazz, Bren and Poppy Xx

Abstract

The creation of an effective construction schedule is fundamental to the successful completion of a construction project. Effectively communicating the temporal and spatial details of this schedule are vital, however current planning approaches often lead to multiple or misinterpretations of the schedule throughout the planning team. Four Dimensional Computer Aided Design (4D CAD) has emerged over the last twenty years as an effective tool during construction project planning. In recent years Building Information Modelling (BIM) has emerged as a valuable approach to construction informatics throughout the whole lifecycle of a building. Additionally, emerging trends in location-aware and wearable computing provide a future potential for untethered, contextual visualisation and data delivery away from the office. The purpose of this study was to develop a novel computer-based approach, to facilitate on-site 4D construction planning through interaction with a 3D construction model and corresponding building information data in outdoor Augmented Reality (AR).

Based on a wide ranging literature review, a conceptual framework was put forward to represent software development requirements to support the sequencing of construction tasks in AR. Based on this framework, an approach was developed that represented the main processes required to plan a construction sequence using an onsite model based 4D methodology. Using this proposed approach, a prototype software tool was developed, 4DAR. The implemented tool facilitated the mapping of elements within an interactive 3D model with corresponding BIM data objects to provide an interface for two way communication with the underlying Industry Foundation Class (IFC) data model. Positioning data from RTK-GPS and an electronic compass enabled the geo-located 3D model to be registered in world coordinates and visualised using a head mounted display fitted with a forward facing video camera. The scheduling of construction tasks was achieved using a novel interactive technique that negated the need for a previous construction schedule to be input into the system. The resulting 4D simulation can be viewed at any time during the scheduling process, facilitating an iterative approach to project planning to be adopted. Furthermore, employing the IFC file as a central read/write repository for schedule data reduces the amount of disparate documentation and centralises the storage of schedule information, while improving communication and facilitating collaborative working practices within a project planning team.

Post graduate students and construction professionals evaluated the implemented prototype tool to test its usefulness for construction planning requirements. It emerged from the evaluation sessions that the implemented tool had achieved the essential requirements highlighted in the conceptual framework and proposed approach. Furthermore, the evaluators expressed that the implemented software and proposed novel approach to construction planning had potential to assist with the planning process for both experienced and inexperienced construction planners.

The following contributions to knowledge have been made by this study in the areas of 4D CAD, construction applications of augmented reality and Building Information Modelling;

- 4D Construction Planning in Outdoor Augmented Reality (AR)
- The development of a novel 4D planning approach through decomposition
- The deployment of Industry Foundation Classes (IFC) in AR
- Leveraging IFC files for centralised data management within real time planning and visualisation environment.

Acknowledgements

I wish to express my profound gratitude to my Director of Studies, Dr David Heesom for his insightful guidance throughout this study. His resolute belief in my abilities and the constructively critical approach he instilled into my research will always be remembered.

My heartfelt thanks go to my partner and soul mate Jess. Her selfless and unconditional love, constantly positive encouragement and unwavering support were fundamental to the successful completion of this study. Also to my children who form the backbone of my motivation for achievement in life.

I would like to thank my Mum and Dad for their financial assistance during the whole of my academic studies and their amazing and constant support with babysitting duties, school runs etc. – thank you.

I must also thank the University of Wolverhampton for the opportunity to expand my horizons and my knowledge by enabling me to undertake this PhD study. Special thanks must go to the School of Technology for their support and funding during the completion of this study. In particular I would like to thank all colleagues and members of staff within the Department of Architecture and Design whom tirelessly encouraged, supported and helped me throughout my studies, especially Dr Kadda Yahiaoui for his guidance and patient proof reading.

Finally I would like to thank the various industrial collaborators and advisors for giving their valuable time and experience during this study, in particular Severn Partnership Ltd for their invaluable input regarding GPS.

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1 Introduction

1.1 BACKGROUND

The creation of an effective, workable construction schedule is fundamental to the timely and cost effective completion of a building project (Staub-French *et al.,* 2008). Indeed, Hendrickson (2008) states that developing a construction plan is a critical task in construction project management, for which planners traditionally use their professional knowledge and experience to define work tasks, estimate the resources and time needed for these tasks and identify any interdependence that exist between them. To this end, tools and techniques such as Critical Path Method (CPM) networks, Gantt charts and 2D schematics of the proposed building are commonly used to both assist the planner's mental processes and help communication and coordination between the various members of the project team (Koo, 2000).

Koo and Fischer (2000) note that this traditional method of construction scheduling is an abstraction of the schedule intent which contains no information regarding the spatial aspect of the project. This leaves the various members of the project team to mentally extrapolate the logical sequence and spatial context of an inherently complex project conveyed only by the Critical Path Method (CPM) schedule and 2D drawings. This, they argue, exposes the whole process to misinterpretation, which in turn can lead to a breakdown of effective communication as each team member involved in the planning and building process develops their own interpretation of the schedule documentation. Furthermore, this traditional planning workflow makes no provision for effectively assessing the quality or workability of the created schedule (Staub-French *et al.,* 2008).

Further to the highlighted technological and process related issues surrounding construction scheduling (Illingworth 2000) states that good scheduling practice starts with a competent and experienced planner. However, studies have shown that there exists within the construction industry a shortfall in the number of experience personnel with sufficient experience to carry out such a task (Kelsey *et al.*, 2000). Allen (2008) points out that in many cases this situation means less qualified personnel, with insufficient experience, are expected to step up to the role in ever increasingly complex construction projects, a view supported by Department of Trade and Industry figures for 2003, where an estimated 50 per cent of failed projects exceeded their agreed contract period (Burrows, 2003 cited in Allen, 2008).

In answer to these shortcomings with the traditional planning workflow and the problems related to the shortage of experienced construction planners, many research efforts since the 1990s have focused upon the 4-dimensional modelling of the construction process as an assistive tool for construction review and schedule communication. This approach, known as

4D CAD (3D plus time), is seen as a natural progression to 3D CAD (Phair, 2000). 4D modelling of the construction project provides the user with the potential to graphically represent the construction process at discrete time intervals by linking the 3D CAD model of a project with the construction schedule (Heesom and Mahdjoubi, 2004; Staub-French and Khanzode, 2007).

Staub-French and Khanzode (2007) elucidate the benefits of utilizing this integrated 4D planning process on real construction projects and note that they have been well documented in case studies such as Haymaker and Fischer (2001) and Kam *et al.* (2003). Researchers have critically examined the functionality afforded by 4D planning and the manner in which it maps onto the needs of the construction industry (McKinney and Fischer, 1998; Koo and Fischer, 2000; Heesom and Mahdjoubi, 2004). Further research into the application of 4D techniques include its use as a tool to foster collaborative working processes (Zhou, 2009),safety planning for a construction project (Chantawit *et al.* 2005), assist with problems associated with site layout and logistics (Ma *et al.* 2005) and work space identification and planning (Heesom and Mahdjoubi, 2004; Dawood *et al.,* 2005). Finally, research into the use of 4D CAD within real time virtual environments has shown the potential for the use of this technology within an interactive environment (Yerrapathruni *et al.,* 2005; Zhou *et al.,* 2009).

1.2 CURRENT STATUS OF RESEARCH AND PRACTICE

The focus of this study is on the use of 4D CAD within an outdoor, wide-area Augmented Reality (AR) environment. To this end; the aim of the study is to address some of the limitations of prevailing research and practice in the area of 4D CAD in relation to real time distributed augmented reality environments, wide area outdoor tracking, model based scheduling and Building Information Modelling (BIM) .

Current approaches to 4D CAD require the user to manually link the elements within a 3D CAD model, representing the Product Breakdown Structure (PBS), and the tasks within a CPM based construction schedule, representing the Work Breakdown Structure (WBS); the output of which is a time-lined simulation of the construction process. Whilst undoubtedly useful for schedule review and constructability analysis, a significant feature of this approach is that it requires the prior creation of a CPM schedule and therefore inherits the significant mental processing associated with this process. Furthermore, despite the voluminous amount of research extoling the benefits of collaborative construction planning, the modus operandi of this approach is as a standalone application for use by one planner in isolation from the multidisciplinary planning team that is a feature of modern construction projects.

More recent research efforts have seen the focus move away from desktop solutions towards application of 4D CAD with immersive Virtual Reality (VR) for interactive review of schedule data in a real time graphical environment. However, while this approach extends the scope of the 4D visualisation to provide real time, real size interaction, it is still predominantly a post planning review tool and as such does not directly address the problems it inherits from the traditional CPM network based scheduling solution. The use of an immersive VR environment removes the real world context that a construction project will inherently occupy and thus could be seen as adding a further layer abstraction. Augmented

Reality (AR) has recently come to the fore of construction research as a tool for contextual visualisation of the product and process of architecture and construction. By utilizing a view of the real environment as a background to the presented visualisation, and by tracking the movements of the user, AR can overlay spatially referenced models or contextual information onto their view of the world to enhance the users understanding of and interaction with the real world.

Further research has sought to address the shortcomings of the traditional planning process by providing a collaborative construction planning environment using a 3D model as an interactive interface for schedule creation. This approach seeks to define a new paradigm for the construction planner by leveraging the benefits of effective spatial comprehension that are afforded by a 3D CAD model, combined with an open-ended social interaction context that allows groups of multidisciplinary planners to work collaboratively towards a robust construction schedule (Zhou *et al.,* 2009).

Building Information Modelling (BIM) and its approach to implementing the Industry Foundation Class (IFC) data model specification have heralded a new era for architectural design, construction planning and building life-cycle management. IFC files describe not only the 3D geometric nature of a building design but are able to capture layers of semantically-rich information such as materials, suppliers and quantities together with inter-element relationships, i.e. parametric constraints. Model-based scheduling is an approach that takes full advantage of the information-rich nature of a BIM which seeks to link architectural design, construction scheduling and quantity take-off into one unified process. However there are issues surrounding the level granularity of a BIM in relation to that of a work schedule to the point where complex algorithms for geometry splitting need to be employed and the new geometric groupings created in this process saved back to the IFC file without affecting the integrity of the original 3D model.

1.3 AIMS AND OBJECTIVES

The aim of the study is to develop a novel approach to computer based construction scheduling through the application of object oriented 4D CAD techniques within an outdoor Augmented Reality environment. It is envisaged that the development of a prototype tool kit will further the applications and practice of 4D CAD simulations, construction planning and the integration of BIM within the design, plan and build workflow.

With this aim in mind, the objectives of this study are:

1. To review the scope of research in the area of construction planning, with particular interest in 4D CAD and emerging techniques such as model based scheduling and Building Information Modelling.
2. To examine current techniques for implementing Augmented Reality within an outdoor environment, to identify and build upon aspects of good practice.
3. To design and develop a research-informed conceptual framework to assist in the identification of the important issues surrounding software development within an AR scheduling context.
4. To propose a novel on-site approach to construction planning and the development of contextual 4D simulations within an outdoor AR environment.
5. To develop a construction planning tool that provides intuitive interaction with an object oriented building model within AR.
6. To determine the effectiveness of such a tool and evaluate its usefulness through evaluation on a conceptual construction project.

1.4 RESEARCH PROGRAMME

In order to achieve the previously specified aims and objectives, the following steps were undertaken.

1. An investigation of current research in the area of construction planning and 4D CAD within the construction industry is carried out to identify relevant issues. Current research and salient industrial initiatives within the area of Building Information Modelling are also critically examined.
2. Formulation of a conceptual framework for interactive model-based 4D construction planning in outdoor AR. During the development of this framework, the key attributes were generated from an analysis of the results of past and current research initiatives.
3. Development of a proposed approach for interactive on-site 4D construction planning. This will include the synchronisation of 3D and Building Information Models to provide a graphical interface for generating scheduling information, enabling the visualisation of 4D CAD simulations in outdoor, wide-area AR and supporting the reading, writing and visualisation of the schedule information to and from the IFC file.
4. The implementation of a prototype software system based upon the proposed approach. The components of the prototype system will encompass the techniques advocated in the proposed approach, whilst also demonstrating the attributes highlighted by the conceptual framework.
5. Formulation of a user evaluation protocol based upon the conceptual framework. Using this protocol, the implemented prototype is evaluated using industry-based practitioners to determine the usefulness of the system and its success in achieving the specified attributes.
6. Discussion and interpretation of the results of the user evaluation and proposal of recommendations for future work in this field.

1.5 STUDY SCOPE AND LIMITATIONS OF WORK

This study seeks to formulate a novel, robust and technologically agnostic approach to construction planning through the application of advanced computer visualisation and data modelling techniques. Through the implementation of the proposed approach, a prototype software tool was developed utilising commercial off the shelf (COTS) technology to enable the formulation of a construction schedule through interaction with a decomposed Building Information Model (BIM). Recommendations regarding the benefits perceived or otherwise, of a particular technological platform or software tool are beyond the scope of this study.

The developed software prototype is a tool for supporting a construction planner towards to development of a schedule and provides no automatic planning functionality. Additionally this approach makes use of IFC as it stands at the moment and makes no additional recommendations for development of IFC standard. Finally the prototype tool utilises a 3D geometry file generated from the same BIM as the IFC file and therefore does not read in geometry from IFC file.

1.6 ACADEMIC CONTRIBUTIONS

Several contributions to knowledge have been made by this study in the areas of 4D CAD, construction applications of augmented reality and Building Information Modelling.

1.6.1 4D Construction Planning in outdoor AR

Augmented reality provides an approach whereby interactive geo-referenced 3D models can be visualised in full scale within the context of a view of a real world location. This can further enhance and democratise understanding of both the design and schedule information. This study advocates the use of 4D CAD techniques for schedule creation through real time interaction with a construction product model. The approach adopted for this study further extends the scope of 4D CAD out of the office by leveraging untethered AR technologies. By employing position tracking technologies that require no preinstalled infrastructure, this approach facilitates ad-hoc outdoor 4D planning and visual construction simulation that could be deployed in context on a proposed construction site.

1.6.2 A novel 4D planning approach through decomposition

The novel 4D CAD approach to construction planning proposed in this study combines the planning and visualisation phases into one iterative and unified activity. This approach facilitates the creation of construction tasks through the decomposition of the construction product model. Construction tasks are created simply by selecting objects within the 3D AR model and assigning date ranges for their construction. Implied construction sequences thus created can be visualised as a 4D simulation for verification throughout the planning process, allowing the planner to verify and amend any sequence errors on-the-fly. This inherently flexible approach provides adaptive 4D CAD visualisations that reflect changes made to the planning sequence in real time.

1.6.3 Deployment of IFC data in AR

The methodology developed in this study provides a novel approach to leveraging intelligent building information data through a real time augmented reality interface. By automatically extracting and mapping a specific subset of BIM data with 3D model elements, this approach facilitates the integration, utilisation, interrogation and interaction with building information data in a real time augmented reality environment. Furthermore, the mapping of 3D elements to IFC objects during initialisation also facilitates asynchronous communication and two-way data flow between the real time environment and the IFC file.

1.6.4 Leveraging IFC files for centralised data management within a real time planning and visualisation environment

The approach developed in this study implements an asynchronous communication mechanism between the real time environment and the IFC data file. This mechanism enables construction schedule data created by the user during the 4D planning session to be written back to the IFC file. To enable communication and collaboration throughout the planning process, the developed software tool can also load existent schedule data from an IFC file for visualisation, verification or revision. This is facilitated by internally organising schedule information data in a manner that is analogous to the objects and relationships relating to planning information within the IFC schema. This novel approach leverages IFC files for capturing, sharing and utilising schedule information in the context of 4D AR construction planning and visual simulation.

1.7 ORGANISATION OF STUDY

This study is comprised of 7 chapters, the outline of which is illustrated in Figure 1-1.

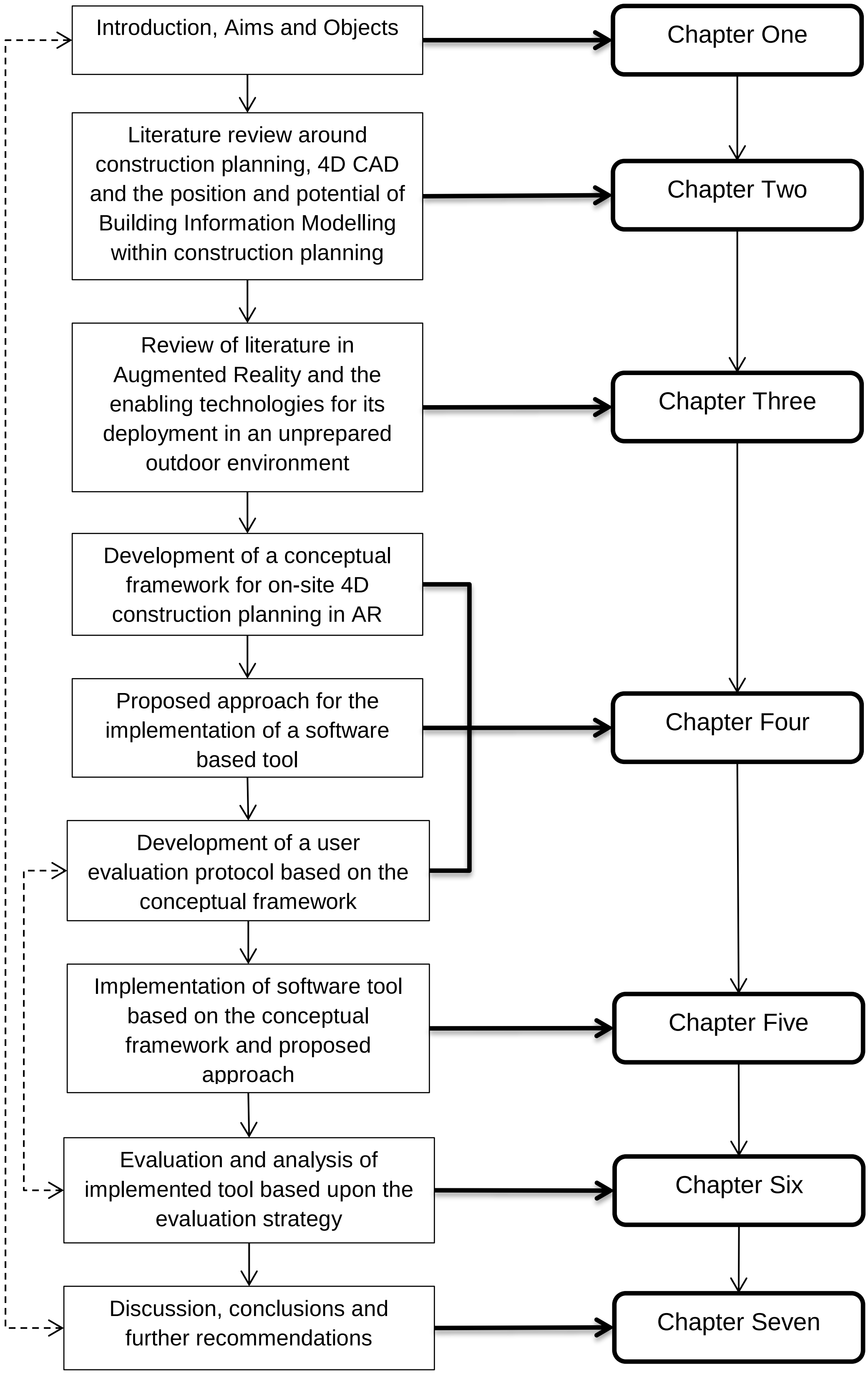


Figure 1-1 Organisation of the study

Chapter 1 provides a general background to this study. It introduces the central rationale and presents the aims and objectives of the research program. An outline of the methodology employed and the contribution to current research that is made by this study is also presented.

Chapter 2 begins with a critical review of current research and industrial practice in construction planning. Following this, the current state-of-the-art in 4D CAD is reviewed. In particular its current potentials, industrial penetration and limitations are examined including virtual planning environments and the position of Building Information Modelling in planning and 4D CAD.

Chapter 3 provides a review of the literature and current and emerging trends in Augmented Reality, with special interest in current and emerging trends relating to the outdoor deployment of this advance approach for contextual visualisation.

Chapter 4 presents the generalised research methodology employed in this study and sets out the developed conceptual framework and proposed approach for the implementation of a novel on-site model-based 4D construction planning tool. In addition, a user evaluation strategy is presented to enable the usefulness and success of the implemented tool to be ascertained.

Chapter 5 provides an architectural overview of the implemented prototype 4D planning tool, 4DAR, based upon the conceptual framework. It details the software design considerations, the developmental and operational concepts that were implemented together with the interfaces, hardware choices and module level processes and functions that constitute the 4DAR prototype.

Chapter 6 presents the results of the user evaluation questionnaire.

Chapter 7 presents a complete review of this thesis and the work undertaken. Its success in achieving the specified aims and objectives is discussed and the significant contributions to knowledge made by this study are presented. Finally, a detailed review of potential future research directions and software improvements are provided.

Chapter 2

2 Construction planning and 4D CAD: Current and future applications

2.1 INTRODUCTION

It is widely acknowledged that effective construction planning is one of the most important tasks in a construction project and is a crucial requirement for its successful completion (Cherneff *et al.,* 1991; Waly and Thabet, 2003; Staub-French *et al.,* 2008). Since the early 1990s, research efforts have shown the potential benefits and insights that 4D CAD techniques can bring to planning process (Koo and Fischer, 2000; Staub-French and Khanzode, 2007).

In this chapter, a critical review of the prevalent construction planning techniques, tools and industrial practice will be carried out. Following on from this will be an examination of the current state-of-the-art of 4D CAD, its dissemination into real construction projects and current and emerging research and industry practice into computer enhanced Building Information Modelling techniques.

Section 2.2 examines salient construction planning techniques, their shortcomings and potentials. Section 2.3 discusses the historical basis of 4D CAD in construction planning, and provides an overview of the key areas in the field including commercial and academic applications of the 4D CAD principles. Section 2.4 provides a discussion around Building Information Modelling (BIM), its origins and its future potentials within the construction industry. In particular, it examines its potential for use in the area of construction planning.

2.2 CONSTRUCTION PLANNING AND SCHEDULING

Waly and Thabet (2003) suggested that one of the biggest challenges facing the construction project team is planning, and that decisions made during this phase impact enormously on the successful completion of a project. In fact, reliable planning has been advocated as nurturing effective collaboration from supply chain through to the work face (Sriprasert and Dawood, 2003). Development of the construction plan can occur at various stages of the design and construction process (Faniran *et al.,* 1999). Indeed the planning process can be further broken down into macro-planning, for decisions made prior to, and micro-planning, for more detailed decisions that are made during the construction process (Waly and Thabet, 2003). However, the net result of the planning process is always to assess the constructability of a proposed building as well as planning and controlling the actual construction process (Cherneff *et al.,* 1991).

McKinney and Fischer (1998) state that construction plans are typically developed to satisfy the cost – time constraints of a project, to communicate the plan to project stakeholders and to decrease the likelihood of costly errors in the construction phase, whereas a construction schedule is the project planner’s interpretation of all the design documentation to produce a coherent set of work tasks and their logical sequential relationships. Cherneff *et al*. (1991) postulate that schedule prediction, planning and control are fundamental for the successful completion of a construction project. They continue the reasoning process that a planner goes through when formulating a schedule must integrate knowledge of current construction practices, costing and productivity together with data specific to the project design. Indeed, de Vries and Harink (2007) states that a construction planner not only needs to possess knowledge and experience of the construction process but must be able to estimate labour and material requirements from the design documentation. However, research by Kelsey *et al.* (2001) suggested that there are a large number of planners without enough experience, knowledge or ability to formulate an effective construction schedule, while Winch *et al.*

(2000, cited in Heesom, 2004) suggests that this may be due to high numbers of experienced planners retiring. To support this, anecdotal evidence cited in Kelsey *et al.* (2001) postulates that at least two generations of planners have come through the ranks without accruing sufficient site experienced to carry out their job.

Effective communication and coordination from schedule creation to implementation is a critical factor of successful project planning (Allen and Smallwood, 2008). However, the inherently fragmented nature of the construction industry, its reliance upon a predominantly document-centric workflow and problems related to software interoperability inhibit communication between project stakeholders, which in turn impacts negatively on coordination efforts (Isikdag and Underwood, 2010). Kelsey *et al.* (2001) give evidence that information provided to sub-contractor planning teams is either deficient in detail or overburdened with an excess of irrelevant information. Evidence cited in Heesom (2004) states that an inadequate flow of information between the various parties involved in the planning process leads to delays in the completion of the construction schedule. While Isikdag and Underwood (2010) state that a system of collaborative working should provide the ability for inter-participant communication whilst allowing all participants to perform their own work in their own way. Furthermore, they postulate that effective collaboration on construction projects is a function of effective information coordination and communication between all project stakeholders. To this end Anumba and Newham (2000, cited in Heesom, 2004) advocate the use of emerging ICT tools for enhancing the communicative and collaborative aspects of working processes.

Typically an initial construction plan outlining the time, cost and resource constraints is prepared at the pre-construction phase. However, once construction work is underway, planners are constantly reviewing the construction progress and adjusting or amending the original plan to correct any deviations from the programmed schedule (Faniran *et al.,* 1999). This level of detail of a plan is an important factor. Too much detail can obfuscate the salient features of the schedule and make it difficult, and is ultimately expensive to maintain or update (Kelsey *et al.,* 2001), in fact Laufer and Tucker (1988, cited in Kelsey *et al.,* 2001) advocate planning at the lowest level of detail possible. Harris and McCaffer (2006) explain that there are two levels of planning: the high level overall strategic plan and the more detailed operational plan. Waly and Thabet (2003) describe these multiple levels of planning as macro and micro planning; macro-planning is concerned with major issues such as the constructability of the design, site layout, resource planning and construction sequencing, while micro-planning typically breaks down these major tasks into a more detailed collection of methods and resources, providing the day to day operations details for on-site work. In this way the detail needed for individual task execution is kept separate from the overall construction schedule. However, they elucidate that the decision making process involved in planning is always the same; an input of project specific data, together with the planner's knowledge and experience, is transformed into an output of actions through an iterative process of manipulation and transformation. The considerable mental processing of information associated with traditional planning practices can easily overburden the planning team, leave the schedule open to multiple interpretations and thus cause problems with effective communication and coordination between the project members (McKinney and Fischer, 1998; Waly and Thabet. 2003; Feng *et al.,* 2010).

2.2.1 Construction Planning Techniques

The construction planner has at his disposal a variety of techniques for creating a construction schedule. This section presents a non-exhaustive review of prevailing methodologies in construction scheduling.

2.2.1.1 Critical Path Method

Created by the aerospace industry, the Critical Path Method (CPM) has been a standard planning method for the construction industry for over four decades (Kelsey *et al.,* 2001; Sriprasert and Dawood, 2003) This activity-centric approach requires the planner to identify work activities, estimate duration and describe relationships between them to formulate a network diagram (Feng *et al.,* 2010). From this, the planner can identify those activities whose completion times control the overall duration of the project. Connecting these “critical operations” forms a critical path of activities through the project that must be “on time all the time”; however a certain amount of flexibility is afforded all other activities (Anthill and Woodhead, 1982). Despite the popularity of this method with construction planners, it has been criticised for its shortcomings over the years. Fischer and Aalami (1996) note that the planner must use his knowledge and experience to describe activity durations and relationships, whereas Kelsey *et al.* (2001) suggest that a major limitation of the CPM network is the lack of inbuilt flexibility pertaining to activity duration. Furthermore, Koo and Fischer (2000) decry the network diagram for creating a layer of abstraction between the planning process and the construction process which provides no reference to the nature of the constraints between the construction activities required or their spatial context. Thus the planner must mentally determine the impact that various factors will have on the project outcome; a task which is not only susceptible to interpretation errors but which also takes a great deal of time to accomplish (Koo and Fischer, 2000).

2.2.1.2 Critical Chain Method

Critical Chain scheduling has emerged in recent years as a viable alternative to CPM-based planning. A direct application of Goldratt’s Theory of Constraints (TOC), critical chain methodology attempts to shorten the overall duration of a project, and address some shortcomings of CPM, by identifying and then exploiting project constraints, such as availability of resources, whilst allowing for uncertainty in task duration (Herroelen and Leus, 2001; Koskela *et al.,* 2010). TOC proposes an approach to project management that identifies constraints or bottlenecks within a system and then seeks to exploit them; however the ultimate goal is to remove the constraint altogether allowing the planner to move onto the next bottleneck in the system (Rand, 2000). A significant feature of Critical Chain methodology is that through optimistic estimation of task duration and the use of project and resource level safety buffers, it seeks to circumvent delays caused by common patterns of human behaviour, firstly that personnel will expand their work task to fill the allotted time (Parkinson's Law) and secondly that due to the perceived likelihood of problems occurring personnel will overestimate the needed duration for an activity (Murphy's Law) (Sriprasert and Dawood, 2003; Herroelen and Leus, 2001). However, Koskela *et al.* (2010) explain this "buffer management" approach does not try to address what has caused the need for buffers, missing the opportunity to reduce process variability and increase productivity.

2.2.1.3 Line of Balance

For projects where there will be a lot of repetitive work, for instance high rise flats or offices, the Line-of-Balance method can prove to be a powerful scheduling tool (Sriprasert and Dawood, 2003; Harris and McCaffer, 2006). Based on the location-based scheduling paradigm, as opposed to the activity-based approach of conventional construction scheduling, Line-of-Balance requires the project to be broken down into physical sections before scheduling can take place; work tasks, described by lines on a diagram, are then created from items on the bill of quantities (Jongeling and Olofsson, 2007). This method focuses on what resources are required for each stage in the project and in doing so attempts to negate each stage's ability to interfere with those following it (Harris and McCaffer, 2006). Features of this technique are its focus on actual progress versus planned progress, maintaining relationships between tasks through inbuilt flexibility (Halpin and Riggs, 1992, cited in Heesom, 2004) and in so doing provide the planner with the ability to perform work-flow analysis (Jongeling and Olofsson 2007). Limitations with this method are that despite the inbuilt buffers for task realignment there is an assumption that the project progress will be purely linear. Furthermore, Harris and McCaffer (2006) note that its inability to be easily updated once work has commenced is a major limitation to its widespread use.

2.2.1.4 Last Planner

An emerging technique within construction planning is the Last Planner system of scheduling, heavily influenced by the lean construction method (Sriprasert and Dawood, 2003). Lean construction is itself based upon the Toyota's Just-In-Time production system and, in contrast to conventional management strategies that seek to optimize the project at the activity level, lean construction is concerned with the effective and efficient flow of information and resources throughout a project (Tommelein *et al.,* 1999). The Last Planner allows planners to generate a record of "what *can* be done", from which workers select tasks – "what *will* be done", a process of system appraisal allows a review of "what *was* done", while all the time steps are taken to shield tasks from the effects of dependences with other tasks. Ultimately, Last Planner is concerned with reducing task workflow and the process-time variability's, leading to increased plan reliability and shortened project duration (Koskela *et al.,* 2010).

2.2.1.5 Planning Presentation

A key component of successful construction planning is communication. A great deal of information regarding work activities, and the complex relationships that exist between them, is conveyed through a construction schedule; this communicative process is vitally important for fostering collaboration between all team members. However, Heesom (2004) explains that a key issue on construction projects is problems with communicating the schedule information, leading to difficulties with implementing collaborative working practices and coordination between the planning team and contractors.

Presentation techniques used for schedule communication are important vehicles for enabling the collaborative and coordinated work practices that are so important for the success of a building project. To date, the conventional methods of presentation such as Gantt charts, bar charts, network diagrams and traditional calendar views are still prevalent within the construction industry. All these methods have their strengths and weaknesses; however Benjaoran and Bhokha (2009) suggest that there is not currently a perfect presentation method for schedule communication. Koo and Fischer (2000) postulate that these prevailing presentation techniques are adequate for communicating ‘who’ will carry out a task and ‘when’ this should occur but lack the context of ‘where’. Furthermore Doulis *et al.* (2007) explain that while the prevalence of 3D models within the construction industry enables effective and intuitive communication of a building’s spatial relationships, they lack the ability to convey the temporal nature of a project. This lack of a spatial context within scheduling documentation or temporal information within a 3D model means project participants must mentally link the scheduled task information with the corresponding physical elements of the proposed building. McKinney and Fischer (1998) suggest that, without any other visual aids, this ‘mental 4D model’, extrapolated from the schedule and design drawings, is the sole representation of the relationships between time and space that exist within the project. Heesom and Mahdjoubi (2004) reveal that site managers and construction planners need to simulate various construction processes during the schedule formulation, while McKinney and Fischer (1998) further elaborate that this mental visualisation effort is often compounded when the implications of design changes on the schedule need to be understood.

2.3 4D MODELLING

The traditional method of using 2D architectural drawings to communicate a structural design to those responsible for the planning and building requires all parties to have a high level of skill and practical experience (Kang and Clayton, 2007). A strange shift in perception must take place as the designer imagines the structure in 3D, but then needs to project it into 2D space to convey its intent to project members, who in turn must mentally, and ultimately physically, transform the lines and symbols back into 3D (Fukai, 2003). Despite the cited prevalence of 3D modelling within the construction industry, there remains persistence with the traditional 2D document workflow; however it been shown that representing a building's design in 3D will provide project members with the most effective tool for design analysis and communication (Riley, 2003). Recent UK governmental policy has lead to the pull of 3D, 4D and Building Information Modelling (BIM) into the UK construction industry (Khosrowshahi and Arayici, 2012), additionally recent research has shown a 75% increase in its uptake within the US since 2009 (Ernstrom *et al.,* 2010).

By linking a project's 3D context with the temporal information within the schedule, 4D modelling, or 4D CAD, outputs a graphical simulation of the construction process (Staub-French and Khanzode, 2007). Thus by explicitly connecting both schedule and CAD data the abstraction associated with conventional planning processes is greatly mitigated (McKinney and Fischer, 1998). 4D CAD simulations can be understood as a visualised link between the 3D elements in a CAD model, the Product Breakdown Structure (PBS), and the construction activities within the schedule, the Work Breakdown Structure (WBS) (Zhou 2009).

4D modelling techniques enhance schedule communication through visual simulation of the construction over time. It has been shown that their creation allows more robust schedules to be generated by allowing project members to accurately visualise, analyse, identify and communicate potential problems relating to the sequential, spatial and temporal aspects of a project, thus reducing rework and improving productivity (Dawood and Sikka, 2008). In addition Staub-French and Khanzode (2007) showed that 4D modelling not only improved communication but assisted with subcontractor coordination by allowing each team member to visualise the relationship their work had with other subcontractors, in addition it helped identify constructability issues and sequencing problems before the project commenced.

Conventionally, a 4D simulation is created by manually linking tasks within a CPM schedule with their corresponding 3D elements using specialist third party software (Collier and Fischer, 1996).This manual linking approach is commonly found in commercial 4D solutions, such as Autodesk Navisworks; however by requiring the input of both a model and a completed schedule Waly and Thabet (2002) argue that this type of 4D CAD should not be seen as a planning tool, while Heesom and Mahdjoubi (2004) note it is still predominantly used as a communication tool. Zhou (2009) postulates that a distributed, interactive virtual environment for synchronous multi-participant planning encourages a more open-ended approach to construction scheduling by providing a workspace with a shared social context. However he further notes that in its current form 4D CAD is predominantly being used for post planning review only.

Heesom (2004) observes that the construction industry has been slow to adopt computer generated visual simulations despite the availability of research elucidating their benefits, while Mahalingam *et al.* (2010) found that there would be less managerial resistance to 4D CAD if it was integrated into their existing workflow. Some researchers have noted that the uptake of 4D CAD by industry has been tardy in comparison with other emerging ICT tools (Bansal and Pal, 2008), while others have proposed that this is because of the addition, perceived or real, of extra processes to the planning workflow (Allen and Smallwood, 2008; Mahalingam *et al.,* 2010). Staub-French and Khanzode (2007) suggest that it is the wide variety of technical, procedural and organisational issues surrounding both 3D and 4D modelling that results in their limited use, while Aouad *et al.* (2000) conclude that it will take a paradigmatic shift in thinking by construction professionals before the benefits of advanced visualisation can be brought to bear in construction projects.

2.3.1 4D CAD Applications

The considerable volume of research efforts into 4D CAD is cited by some as evidence of its potential for usefulness on construction projects (Staub-French and Khanzode, 2007). Indeed many research studies support and extend this view. Koo and Fischer (2000) demonstrate how 4D modelling not only allows the workability of a schedule to be evaluated but also promotes interaction and collaboration between project members. Haymaker and Fischer (2001) illustrate how it assisted with creating, analysing and communicating the schedule, while proving itself as a valuable team building tool. Kang *et al.* (2007) further show how a collaborative web-based 4D visualisation allowed geographically dispersed personnel to work more effectively, whilst Staub-French and Khanzode (2007) reveal how 3D and 4D modelling increase productivity, reduce rework and lead to a reduction in overall project duration.

Much research over the years has seen the development of 4D CAD models and simulations for a variety of construction-related problems. Waly and Thabet (2003) propose virtual construction rehearsal as a method for schedule creation within a Virtual Construction Environment (VCE). The sequence is captured from the order in which components in the product model are transferred to an adjacent empty window within the Interactive Virtual Interface (see Figure 2-1); this manual ‘drag and drop’ scheduling mechanism utilizes the planners knowledge and experience, and augments it with a knowledge base of available means, methods and resources that support the generation of the construction schedule (Waly and Thabet, 2003). 4DCAD-Safety is a planning review tool that seeks to integrate safety planning with construction simulation. Using AutoCAD for visualisation, MS Project for schedule creation and a database to store all product, process and safety information, a significant feature of this approach is how it attempts to support the work of the safety planner through the provision of a context-driven safety library (Chantawit *et al.,* 2005).

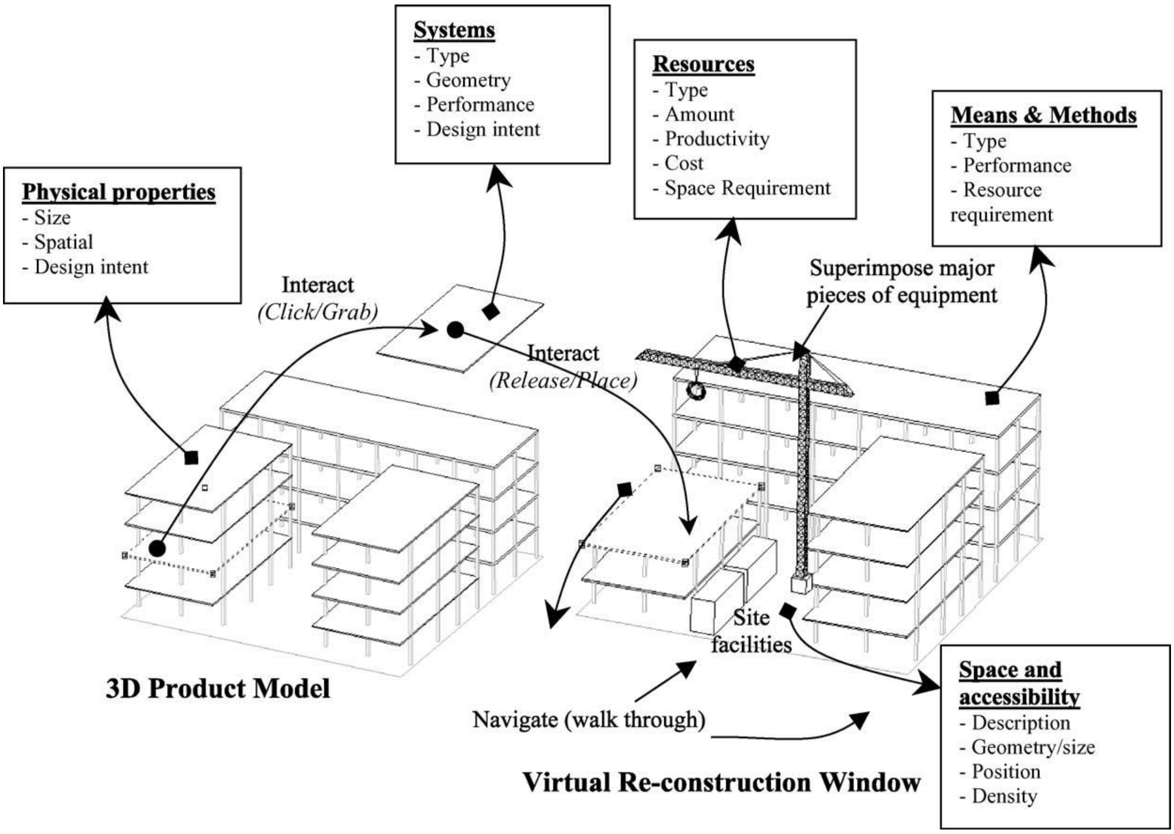


Figure 2-1 Capturing sequence and task information from user interactions (Waly and Thabet, 2003)

Recent research efforts have sought to extend 4D CAD, adding extra layers of information to the product model. One such example puts forward the concept of a BIM-driven virtual 5D planning and construction simulation environment that includes cost as the fifth dimension (Popov *et al.,* 2010). A proposed *n*D modelling tool further extends the dimensionality of the product model with decision-supportive information such as cost, sustainability, energy requirements and even life-cycle maintenance; while the ability to clearly visualise the relationship between design, resources and project constraints enables ‘what-if’ analysis of various design perspectives (Lee *et al.,* 2005). As an alternative to the ubiquitous CAD environment, Bansal and Pal (2008) leverage the ability of Geographical Information

Systems (GIS) to create their 4D model and maintain a spatially referenced database to store the component–task link information. A feature of this approach is the automatic creation of the 3D model and the dynamic schedule linking mechanism that quickly reveals missing work items and logical errors within the planned sequence (Bansal and Pal, 2008).

The following sections set out a discussion around standard and emerging functionalities of 4D CAD, its industry usage, and current and emerging research in the field.

2.3.1.1 4D Visualizations

By mapping a task's schedule information to the corresponding elements in a 3D model, 4D CAD can provide clear visualisation of the schedule intent (Dawood and Sikka, 2008) and thus enables both technical and non-technical stakeholders to fully comprehend the information conveyed within the construction documentation (Golparvar-Fard *et al.,* 2009). This democratisation of the schedule information enables all participants to appreciate the spatial, temporal or sequential aspects of a project, whilst facilitating inter-team communication (Dawood and Sikka, 2008).

Kang *et al.* (2007) propose that 4D visualisations facilitate the resolution of sequencing problems in advance, indeed they go on to show that by using 4D computer visualisation, a planning team was able to detect more logical errors, more accurately and in less time than a comparable team using 2D graphics. Liston *et al.* (2001) report that, in contrast to paper-based meetings planning, teams using 4D CAD spent less time describing information but more time explaining it (Figure 2-2 and Figure 2-3). They continue that through shared interactive visualisation of the project information, 4D CAD effectively communicated the spatial and temporal relationships conveyed through the project documentation and thus enabling the planning team to quickly identify and solve problems.

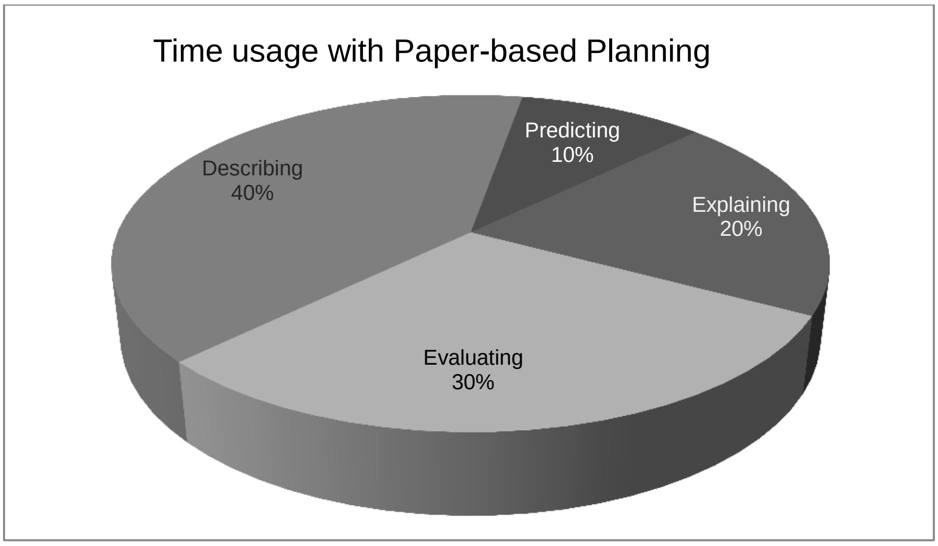


Figure 2-2 Paper-based Planning (Liston *et al.,* 2001)

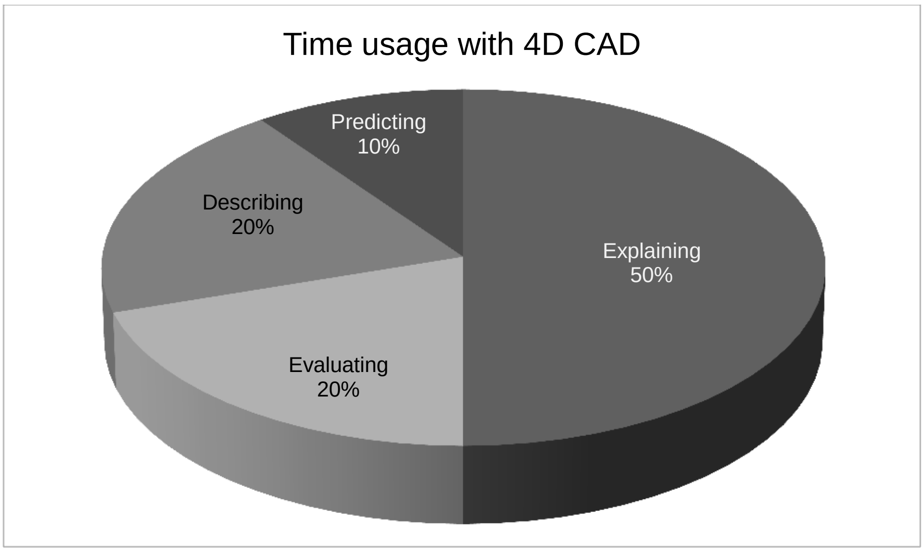


Figure 2-3 Current 4D CAD (Liston *et al.,* 2001)

Several studies give examples of 4D visualisation being used on real construction projects. Haymaker and Fischer (2001) describe how using 4D modelling on the Walt Disney Concert

Hall project enabled the team to discover errors in the schedule that were missed when using the CPM-based Gantt chart. They also clarified how it enhanced communication and collaborative working between the various team members involved in planning the construction. Using commercial 3D modelling and scheduling applications with a 4D simulation module purpose written at the Center for Integrated Facility Engineering (CIFE) at Stanford University, this study also reports that inconsistencies with the layering and naming conventions, and differences in level of detail and granularity of building elements between the architectural model and the scheduled tasks needed to be resolved by the 4D modeller, something that proved to be a very time consuming process.

In a study that examined the viability of using 4D CAD on construction projects, Koo and Fischer (2000) used commercially available 3D and 4D modelling software to create a schedule simulation from an *a priori* CPM-based schedule and 2D architectural drawings. They concluded that the 4D model was an effective means of enabling even inexperienced personnel to analyse the design and schedule, and identify problems relating to constructability and sequencing by unambiguously representing the spatial and temporal complexities of the project. Furthermore, they note that, by integrating the design and construction information into one visual simulation the 4D model supported interaction and collaboration between team members. Time taken for preparation, however, was also an issue in this study, with the added task of creating a 3D model from 2D drawings proving to be the most time consuming at almost 70 man-hours out of a total preparation time of 104 man-hours. To offset this considerable amount of modelling work and rework, they propose building the 4D model in the design stages to decrease the lead-in time for creation of the 4D simulation (Koo and Fischer, 2000).

Previous citations reveal the importance of creating the 3D model during the design phase to avoid unnecessary extra work during the generation of the 4D simulation. This relationship between 3D and 4D modelling is further explored by Staub-French and Khanzode (2007) who present a set of guidelines for their combined implementation. In two projects that the authors were involved with, the Camino Medical Group (CMG) and Sequus projects in California, the team members used various object-based parametric 3D modelling tools and commercial 4D applications to communicate and collaborate during the design and planning stages. It is reported that, even though the 4D modellers needed to rearrange the 3D elements into selection sets (CMG) or the layers of the CAD model (Sequus), working in this way kept cost growth to a minimum, increased productivity, enabled pre-fabrication and decreased the overall duration of the project by eradicating clashes on site and thus reducing the need for rework. It is further postulated that issues such as needing all contractors and sub-contractors to know and use compatible design software or the reported increases in design time were offset by benefits felt on site such as fewer change orders and less requests for information.

With 4D CAD tools having been shown to assist the planning team understand the full scope of a construction project various software houses are now marketing robust, mature 4D CAD applications, such as Autodesk’s NavisWorks, SmartPlant Construction from Intergraph and Bentley’s ConstructSim. These applications provide 4D solutions that are well integrated within the standard planning workflow and software pipeline of a construction project. However, they are still predominantly used as a tool for visualisation with little scope for enabling construction analysis (Heesom and Mahdjoubi, 2004).

2.3.1.2 Simulating and Automating with 4D CAD

4D CAD enables the visualisation of a constantly evolving construction product at discrete time intervals by animating the transformation of space (3D model) over time (construction schedule) (Kamat and Martinez, 2001). As a complementary alternative to this schedule-based product level approach, some research efforts have proposed the visualisation of construction at the operations level using Discrete Event Simulation (DES) linked to a 3D model (Kamat and Martinez, 2002; Märki *et al.,* 2006; Behzadan, 2008). By enabling the interplay of resources such as labour, materials and equipment, together with the evolving construction product to be incorporated into the simulation model, this approach has the potential to communicate not only the 'what, 'where' and 'when' of construction activities but also the 'who' (will build it) and the 'how' (it will be built). Similar to DES but differing in scope, virtual prototyping describes computer simulation of an actual or proposed product (product model), that can be analysed and tested in relation to aspects of its lifecycle as if it were a physical model (Wang, 2002). However, despite its successful application in the aerospace and automotive industries, its application within the construction industry for product-process simulation has been very limited (Huang *et al.,* 2007). In this respect Huang *et al.* (2007) proposed a Construction Virtual Prototyping system built around Dassualt Systeme 'V5' modelling and simulation platform. Using the platform's "Product-Process-Resources" (PPR) paradigm within its product modelling and process simulation software (CATIA and DELMIA), the authors produced detailed, multi-constrained simulations of the construction sequence. Feedback from industrial usage highlighted that while its use assisted constructability analysis, schedule creation and process optimization, tedious data input procedures and the difficulty in modifying the simulation were cited as potential drawbacks of this approach. Flood (2010) explains that while DES techniques provide powerful and versatile tools for construction analysis and planning, it is the amount of time and effort needed to create and validate a simulation model that precludes its use on most construction projects. Others suggest it is the uniqueness of each construction project's context, resource requirements and constraints that have limited the application of virtual prototyping approached within the construction industry (Huang *et al.,* 2007).

It is a commonly held view that the *a posteriori* generation of a 4D simulation from the CPM schedule relegates its purpose from a planning tool, to a tool for post scheduling review only (Waly and Thabet, 2003; Zhou *et al.,* 2009). One answer to this cited shortcoming with current 4D CAD efforts is to extrapolate the construction sequence directly without the input of a schedule. To this end, de Vries and Harink (2007) proposed a system whereby a schedule is created automatically from the inputted 3D model only. Converting the line-based entities in a CAD file into solid geometry models allowed the developed algorithm to use the Boolean intersect operation to examine the physical relationships between model elements and thus derive a construction sequence. Of note is this system’s incapacity to account for the constraints on time, materials, labour or cost that exist on a real construction site, and therefore while the generated sequence of activities was correct, the predicted duration was significantly shorter than in reality.

Since work during the early cybernetics movement of the 1960’s (Goldberg and Holland, 1988), numerical optimisation algorithms based upon observations of natural selection and genetics have been successfully applied to a wide variety of scientific and industry-based research problems (Feng *et al.,* 2010). These Genetic Algorithms (GAs) operate upon a population of possible solutions initially classifying each one according to its potential suitability; then, using heuristic search methods, candidate solutions are selected, recombined and mutated in a manner that mimics the mechanisms of natural selection to arrive at a robust solution even with large and complex problems in areas as diverse as image processing and robotics (Coley, 2001). This ability to arrive at an optimum solution for a complex problem has led to GAs being specified in some construction research for automatic schedule creation. Within the proposed Interactive Toolbox for 4D-Modeling, the network plan is created automatically by a DES module; tasks are represented as a series of genes within chromosome-like sequences which are combined, recombined and mutated by the Genetic Algorithm Process Optimization (GAPO) module to optimize the schedule in terms of time, cost or resource constraints (Märki *et al.,* 2006). Feng *et al.* (2010) use a similar chromosome metaphor to describe possible construction sequences. This approach extends a Building Information Model (BIM) by associating hierarchical work item codes (WBS) with each design element which are then arranged within an ‘object sequencing matrix’. A number of possible sequences are thus created and ranked based on the physical dependencies described within the matrix, which are then passed through the GA to generate a time-cost integrated schedule.

Heesom (2004) developed a 4D application to assist with the problems of space planning on construction sites. A mechanism is provided for reorganising the granularity of the model elements through decomposition or grouping, while the use of Unified Classification (Uniclass) product codes in the CAD model enabled automated linking of PBS and WBS. Similarly Uniclass codes were used on the VIRtual CONstruction site (VIRCON) project to enable some automation of the linking mechanism between product and task (Dawood *et al.,* 2005). This integrated database-driven approach used the Uniclass specification to define PBS – WBS relationships within the 4D model. Integration of construction task and site layout planning within a 4D simulation environment was advocated in Ma *et al.* (2005). Prior grouping of 3D CAD objects by WBS code effectively enabled automatic task-object links to be created; these are then mapped against a database of standard work tasks, enabling automatic schedule generation to be attempted. These examples illustrate how the addition of semantic information to the elements within a CAD model enabled automatic linking of product and process; however while this approach provided extra functionality within its individual applications, it does not promote the sharing of this data with other 3D and 4D systems (Ma *et al,.* 2005), correspondingly Heesom (2004) advocates using a standard formalised product model to enhance data exchange between all project stakeholders.

Computer-assisted approaches to 4D modelling and planning present strategies for alleviating much of the time consuming work associated with conventional 4D CAD approaches. However, while automating the connection of component and process relieves the planner from this tedious task, completely automating the whole planning process removes all user-system interaction and negates the planners knowledgeable and creative input into solving each inherently unique scheduling problem (Waly and Thabet, 2003; Zhou *et al.,* 2009). To address the well cited problems with conventional 4D ‘review’ tools and yet retain the creative input of the planner, Zhou *et al.* (2009) proposed to facilitate multidisciplinary teams of planners to each generate their component schedules through direct interaction with a common 3D model in a distributed real time environment.

2.3.1.3 Collaborative 4D Planning

The increasingly global nature of the construction industry has already created a need for personnel in different geographical locations to work collaboratively (Faraj *et al.,* 2000). Moreover, it has been shown that the effectiveness of collaboration and communication efforts within a project are improved through proper coordination (Ellis *et al.,* 1991). Some research efforts suggest that effective collaboration can only occur through effective coordination and communication of the project information (Isikdag and Underwood, 2010), while others elucidate that true collaborative planning is a result of combining collaborative and communicative work practices with 4D CAD principles (Heesom and Mahdjoubi, 2004).

Fukai (2003) suggests that the level of communication and coordination that is required between the various trades and professions when creating a 4D simulation goes beyond the idea of visualisation or collaboration, claiming it is more akin to the workflow on a construction project. Conventional practice in the construction industry involves the ad hoc creation of a multi-discipline teams brought together only for the duration of the project, and as such, requires determined coordination and collaboration efforts (Isikdag and Underwood, 2010). Zhou *et al.* (2009) note this need for collaboration is just as evident in multidisciplinary planning teams, while it is further suggested that current commercial 4D tools are predominantly stand-alone solutions and therefore do not fully support collaborative work (Zhou *et al.,* 2007).

While some research has alluded to the fact that early ‘Visual 4D CAD’ applications stimulated and fed into the development of current ‘Collaborative 4D CAD’ efforts (Webb, 2000), it is evident from the research that conventional 4D CAD already has the potential to promote collaborative working practices (Koo and Fischer 2000, Haymaker and Fischer, 2001; Fukai, 2003; Dawood and Sikka, 2008). Several other research efforts have sought to further the use of 4D CAD by building on its potential to improve communication and coordination within the context of collaborative working environments. Kang and Clayton (2007) provide experimental evidence on the potential benefits afforded the planning process by collaborative web-based 4D planning and visualisation. They show how through web-based chat and browser-based visualisation of the construction sequence, this distributed web-based planning tool enabled team members at different locations to quickly and accurately find more logical errors, with less communication time than when using 2D representation of the design. Zhou *et al.* (2009) postulate that prevailing 4D CAD applications are for planning review rather than for schedule creation, however by providing real time distributed interaction with a unified 3D model, it is suggested that collaborative 4D CAD can provide geographically dispersed planning teams with a shared social context in which they can leverage individual and social creativity towards the generation of a robust construction schedule. Focusing on interaction with a shared 3D model within a networked environment, this distributed 4D planning tool utilizes an ‘interactive definition’ method of schedule creation. This approach enables members of a multidisciplinary planning team to work individually on their corresponding parts of the unified 3D model, whilst interacting with other team members, in a real time ‘open social-technical’ setting (Zhou *et al.,* 2009).

Computer-Supported Cooperative Work (CSCW), a term first coined in 1984 by two researchers at MIT, is an emerging and interdisciplinary field whose definition is still in a certain state of fluidity and as such a certain amount of debate still exists surrounding it’s definition and focus (Schmidt and Bannon, 1992; Mills, 2010). Bringing together social and computer sciences, CSCW attempts to bridge the gap between human-computer and human-human interaction and seeking to establish enabling technologies that promote the dynamic nature of group working. Schmidt and Bannon (1992) clarify its focus as seeking to understand the nature and requirements of cooperative work with the objective of designing computer-based technologies for its support. Mills (2010) identifies ten dimensions that are integral to the CSCW or groupware design process: time, space, group size, interaction style, context, infrastructure, user mobility, privacy, participant selection, and system extensibility. Further to these design considerations, research in this field has identified five essential features that should be incorporated within a CSCW-based application: communication, configuration, coordination, information access and interaction (Mills, 2010). Schmidt (1990, cited in Schmidt and Bannon, 1992) elucidates that while the rationale behind cooperative work can be to simply augment mental and physical processing capacities or to combine workers from various specialized fields, it is through incorporating and building upon the team’s variety of strategies, perspectives and conceptions that CSCW facilitates a balanced unbiased problem solving approach and mirrors the inherently diverse nature of a modern work environment. The Shared Space project (Billinghurst *et al.,* 1998) sought to exploit new interface techniques within shared Virtual Environments to enable

CSCW within an Open Shared Workspace. Some research has also advocated the application CSCW principles within a real time, distributed, 4D planning environment to promote and enhance collaborative construction schedule creation (Zhou *et al.,* 2007; Zhou *et al.,* 2009).

2.3.1.4 Virtual Planning Environments

Advanced visualisation techniques, such as Virtual Reality (VR), have long been utilized in construction research to enhance information communication and improve pre-construction evaluation of the design and schedule (Sriprasert and Dawood, 2003). VR is a technological approach that allows users to navigate around a Virtual Environment (VE) in 3D and interact in real time with large and complex visual data sets (Woksepp, 2007). This ability to represent complex spatial information intuitively makes this technology very well suited for enabling a shared and robust understanding of a proposed construction schedule (Woksepp *et al.,* 2005). Zhou *et al.* (2009) used a semi-immersive distributed VR environment to enable geographically disparate planners and contractors to interact with each other and a shared 3D model in real time during the schedule creation. While the use of an immersive VR-Experimental Virtual Environment on the Helsinki University of Technology Auditorium Hall 600 project nurtured efficient communication of the planned design between all stakeholders, real time visualisation of the 4D model promoted awareness of potential issues regarding the constructability (Kam *et al.,* 2003). Doulis *et al.* (2007) suggest that the ability of immersive VR technology to convey the spatial characteristics and relationships of a project intuitively, and at a realistic and natural scale, has almost predetermined its use for visualising the construction process.

Despite the published benefits and insights gained from real time 3D environments and the integrated visual communication approach they enable, there is a reluctance within the AEC industry to adopt new workflows and technologies that are not yet seen as having direct business benefits (Aouad *et al.,* 2000). However, this reluctance could also be attributed to the perceived amount of time needed to learn new software approaches and interfaces, which itself results from a general unfamiliarity with these technologies within the construction industry (Doulis *et al.,* 2007).

In an in depth assessment of the role of visualisation and process modelling within the construction industry, Aouad *et al.* (2000) reinforce that 3D and VR technologies are a useful conduit for communicating, integrating and visualising the project information. They further elaborate upon this by identifying four construction processes of which three experience direct benefits from real time 3D visualisation. During the briefing stage interaction with a VR model assisted with procurement. During the design phase it enabled visual verification of design consistency, constructability assessment and clash detection, while visualising cost and time in VR is proposed once construction is underway. However, an empirical study that surveyed 103 construction professionals revealed that while most considered Virtual Reality to be a good or excellent communication medium, about half of all respondents also said that they only spent between zero and five per cent of their time creating or viewing visualisations of any kind (Aouad *et al.,* 2000).

Haymaker and Fischer (2001) reported how by combining Virtual Reality technology with 4D CAD during the Walt Disney Concert Hall Project, multidisciplinary groups of stakeholders were able to concurrently and collaboratively review construction strategies. Using an immersive virtual environment, this real time interactive 4D simulation enabled the team to assess the workability of the schedule by visualising its progress at daily increments, deliberate upon project constraints and identify and resolve issues prior to construction starting (Liston *et al.,* 2001). It is further reported that the shared social context of the virtual environment enabled intuitive interaction with project information, improved the focus of team members, better communicated the relationships and dependencies with the project and proved to be an overall valuable team building exercise (Liston *et al.,* 2001; Haymaker and Fischer, 2001).

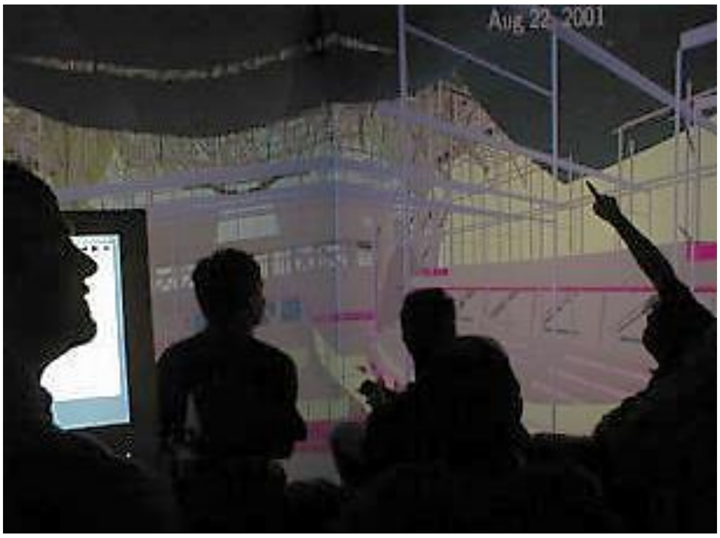


Figure 2-4 Planning team collaboration in the VR Cave. (Haymaker and Fischer, 2001)

An investigation into the viability of using an Immersive Virtual Environment (IVE), for viewing and creating 4D visual simulations, reports how significant time savings were made over the conventionally generated schedule when construction professionals collaborated within the IVE (Yerrapathruni *et al.,* 2005). It was reported by the users that not only did the ability to visualise within the IVE enabled a better understanding of constructability issues and possible solutions, but the improved spatial awareness it afforded them provided the insight to develop a more parallel approach to work assignment.

In a case study reporting on the use of VR and 4D CAD during the design and construction of a major new facility at a large Swedish mining company, Woksepp *et al.* (2005) report that real time visualisation of construction and site operations improved coordination and collaboration between all stakeholders, increased the understanding of the projects spatial constraints, and enabled a more robust understanding of the impact of decisions on project process. Doulis *et al.* (2007) provide a further example of combining advanced visualisation techniques with construction process simulation. Developed as a conceptual interface for construction process visualisation in VR, the proposed 4DIVE system is designed for interactive visualisation of 4D models within an immersive, rear projection, stereoscopic VE.

While research has proven the ability of VR to provide communication-enhanced, real time, real scale visualisation of the construction within an interactive virtual environment, the emerging field of Augmented Reality provides the possibility of contextual visualisation and interaction with a 4D model. Immersion within a full-scale VE has been shown to assist with visual comprehension and communication of the construction schedule; however it is proposed here that removing the real world context from the user's field of view not only abstracts the context of a project, but precludes the safe use of VR for on-site planning. Related to VR technologically, but differing in scope, Augmented Reality (AR) is a computer-based visualisation technique that has more recently come to the fore in construction research. But while VR deducts reality from the users experience, AR enhances a user's perspective on the world by augmenting the real view with virtual objects registered in the real world coordinate frame, so they appear to co-exist (Azuma, 1997; Azuma *et al.,* 2001). Indeed, Aziz *et al.* (2009) elucidate upon the future benefits for the construction industry through the application of such context aware computing techniques as AR.

Much construction related research efforts have seen the application of indoor AR technology for a variety of purposes. Architectural Anatomy is an indoor AR system that augments the user’s view of a building with spatially referenced images of hidden structural elements, such as rebar configurations and columns, with corresponding structural analysis data (Webster, 1996). AR CAD (Dunston *et al.,* 2002; Dunston and Wang, 2005) uses fiduciary markers with vision-based tracking to allow real time, in-place visualisation and analysis of aspects of construction design. Applications of AR for heavy construction equipment operator training (Wang and Dunston, 2007) and evaluating earthquake-induced building damage (Kamat and El-Tawil, 2007) have also been proposed. Golparvar-Fard *et al.* (2009) propose overlaying time-lapsed photographs showing the as-built condition of a construction site with an as-planned 4D simulation model for construction progress monitoring.

Despite the many examples of AR in construction research, instances of 4D CAD applications in AR remain rare. A4D (Dias *et al.,* 2003) is such a proposed system that provides an interface between the design and construction process within a Distributed Virtual Environment (DVE). This distributed real-time augmented 4D system seeks to link all stakeholders, designers, engineers and contractors involved in the planning process with a web-accessed ‘Building Construction Database’ for storing, organising and controlling project related data. Collaboration within the DVE towards the creation of the 4D simulation uses marker-based, tangible, interaction devices for picking, manipulating and transforming the virtual components in the 3D model. However, despite reference to an indoor-outdoor mobile AR approach, this application does not currently support outdoor AR, providing only a marker-based tracking and interaction paradigm within an indoor setting.

More recent advances in areas such as mobile computing, digital video, wireless networks, GPS and other position tracking technologies have seen the development of usable AR-based tools for outdoor construction applications. One approach uses marker-less vision-based tracking in an interactive outdoor AR application for in-place visualisation of a 3D architectural model on a mobile device (Honkamaa, 2007). A feature of this model review tool is that through interaction with a touch screen mobile device, the user is able to fine tune the model's position and orientation, or manually place the model in the scene in the absence of GPS positioning data. A further example extends work into DES and construction simulation (Kamat and Martinez, 2002) into an outdoor AR environment for the visualization of 3D animations of construction operations (Behzadan and Kamat, 2005; Behzadan, 2008).

Hakkarainen *et al.* (2009) describe a modular software framework for 4D visualisation and interaction with Building Information Models in an outdoor AR setting. This OpenSceneGraph (OSG) based AR prototype is comprised of three core modules: 4DStudio handles the time aspect of the project that is created *a priori* and read in from a project planning tool, MapStudio geo-locates the building model using Google Earth API and maps the output from a GPS and compass module to keep it registered in 3D space, while the OnSitePlayer module handles on-site visualisation and interaction with the BIM. An interesting feature of the approach is the inclusion of a module for thin-client, on-site visualisation. Through real-time communication with a server, a 2D projection of the building model is produced from the client's Point Of View (POV), only being updated if changes in the user's position or orientation fall outside of pre-set parameters. However, it can be seen that this approach to 4D CAD in AR, whilst functioning at a high level and offering novel interaction and visualisation mechanisms, adheres to the conventional approach of needing the input of an already completed project schedule and as such, whilst providing a contextual schedule review tool, does little to assist the planner with the task of schedule creation.

2.4 BUILDING INFORMATION MODELLING

Despite the well documented importance of communication and its ability to foster coordinated and collaborative working within the construction sector, industry fragmentation, problems with data exchange and an industry-wide reliance upon a document-based way of working have prevented the construction industry as a whole from moving towards a more coordinated, communication-rich working practice (Heesom, 2004; Allen and Underwood, 2008; Isikdag and Underwood, 2010). As a method for addressing these issues with integration, interoperability and collaboration, and inspired by the computer integrated manufacturing (CIM) approach of the aeronautical and automotive industries, Building Information Modelling (BIM) is an approach to design and construction informatics that seeks to streamline the manner in which data is shared within a collaborative work environment (Vanlande *et al.,* 2008; buildingSMART, 2010; Sacks *et al.,* 2010; Grilo and Jardim-Goncalves, 2010).

Vanlande *et al.* (2008) explain how BIM represents a process for generating, storing, managing, exchanging and sharing building information in such a way as to promote integration, interoperability and collaboration within the construction industry. Grilo and Jardim-Goncalves (2010) concur that rather than being an actual model, BIM is a dynamic process that supports the creation of collaborative working environments, while further studies postulate that BIM is a system that facilitates integration and reuse of building information and domain-specific knowledge throughout the whole lifecycle (Lee *et al.,* 2006). The Associated Of General Contractors of America (AGC) guide to BIM implementation defines it as a data-rich, object-oriented, intelligent and parametric digital representation of a facility (Ernstrom *et al.,* 2010). Researchers at Salford University postulate that a BIM contains two distinct types of information. Firstly, it describes a building's components with their corresponding real-world attributes and secondly it holds information regarding the physical relationships and constraints that exist between them (Fu *et al.,* 2006). A recent case study reporting on the use of BIM throughout the design and planning stages of a construction project identified six benefits from implementing its integrated approach, including rapid visualisation, better decision support and improved communication throughout the project team (Manning and Messner, 2008). Isikdag and Underwood (2010) suggest that the most significant industrial benefit from the use of BIMs is efficient data exchange and sharing throughout the life-cycle of a building, while others have noted it's potential to assist in the management of construction projects (Bryde *et al.,* 2013)

The increasingly prevalent BIM-based approach across the construction industry has further promoted the need for integration and interoperability between the various modelling applications used by designers, contractors and specialist trades (Khemlani, 2004). Lee *et al.* (2006) elucidate that 3D 'knowledge-rich' parametric modelling systems are central to the implementation of BIM and throughout the lifecycle of building information. In contrast to the purely geometry-based approach of traditional CAD applications, such as Bentley MicroStation and Autodesk's AutoCAD, BIM-based CAD systems, such as ArchiCAD from Graphisoft and the Revit suite of programs from Autodesk, offer an object-oriented, product model-based approach in which building elements, such walls, slabs, doors and windows are the basic drawing components used in the models creation (Fu *et al.,* 2006). However, as these commercial BIM-based solutions predominantly use a proprietary data model for internally organising and storing building information, they do not add value to the effort for interoperability within the design and build chain without the use of API-level translators and program-specific importers (Khemlani, 2004).

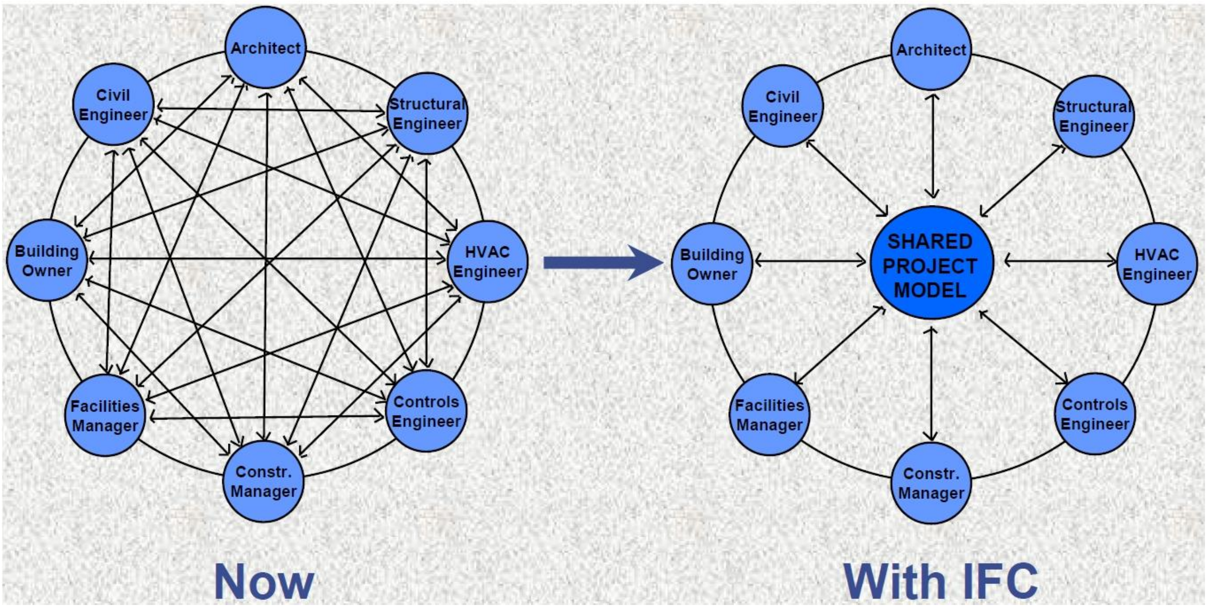


Figure 2-5 The IAI's vision towards an Integrated Project Model. (Kiviniemi, 2006)

Developed since the mid-1990s by the Industrial Alliance for Interoperability (IAI) as a way of improving information sharing and productivity throughout the whole building lifecycle (Kiviniemi, 2006), the Industry Foundation Class (IFC) is an object-oriented, building-specific data model that, as an open non-proprietary format, offers the potential for sharing building information independently of commercial tools and proprietary file formats. Offering the possibility of a more integrated, centralised mode of working within the construction industry (Figure 2-5) through improved software interoperability, IFCs are based on STEP (STandard for Exchange of Product model data) which itself is governed by ISO 10303 and is represented using the formal computer-readable EXPRESS modelling language. In addition to a building’s physical components, such as doors, walls and slabs, IFCs provide the capability to capture information relating to less tangible project concepts such as space volumes, construction costs and schedule activities. However, whether tangible or intangible, all entities can possess a number of attributes relating to such things as product name, materials, finishes, inheritance, relationships or geometric representation (Faraj *et al.,* 2000; Khemlani, 2004; Fu *et al.,* 2006; buildingSMART, 2010; Grilo and Jardim-Goncalves, 2010).

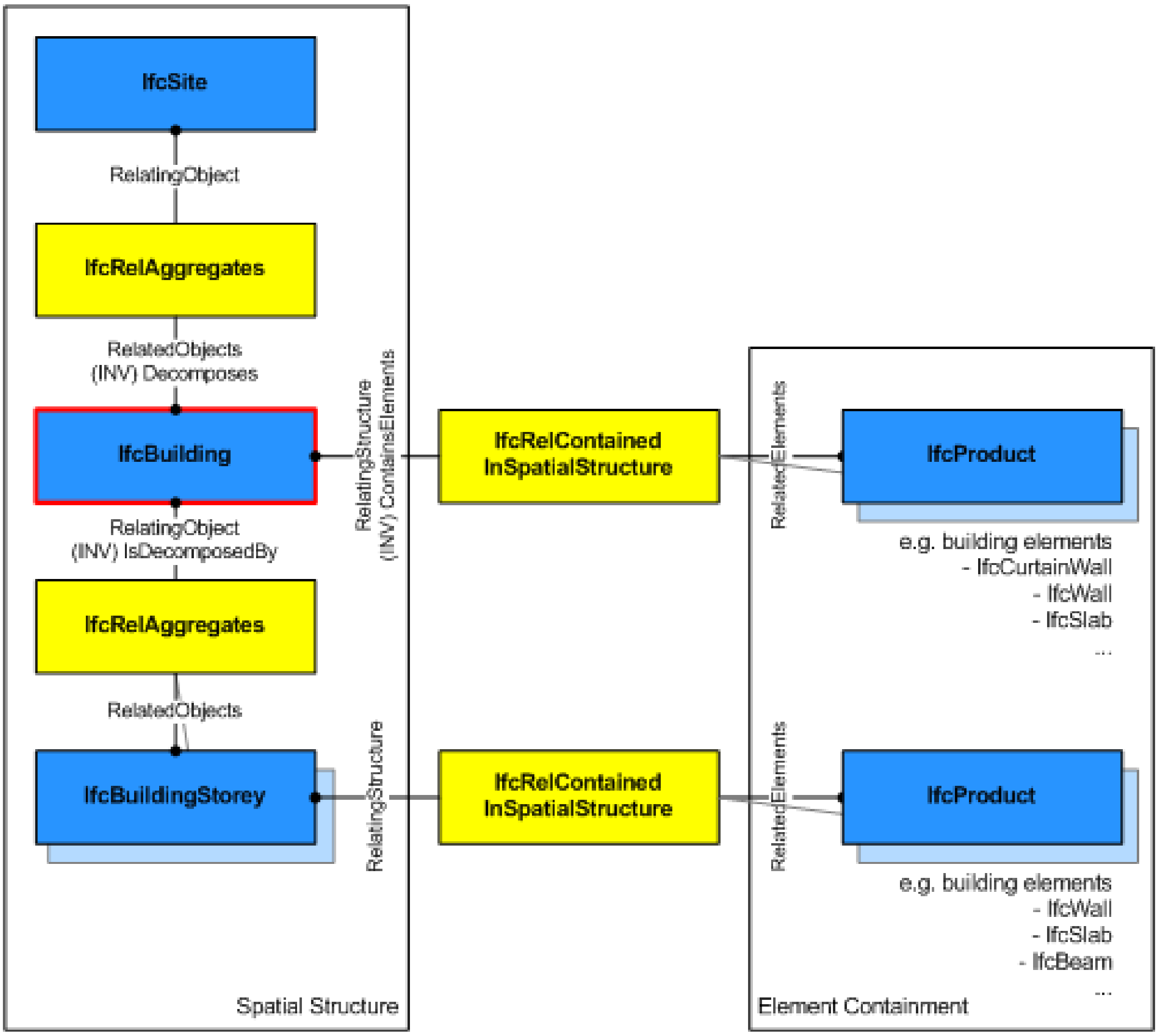


Figure 2-6 Overview of a buildings spatial structure, building elements and corresponding relationships defined within the IFC schema (buildingSmart 2007)

Figure 2-6 shows the heirarchical, object orientated approach to modelling a building's structural information that is afforded by IFCs representation of a BIM. Further, this approach is extended into the area of construction scheduling. Within the IFC schema, there are defined entities for capturing individual work tasks and their respective constraints within a work schedule. Relationships are also defined that link these elements together and enable the aggregation of building elements to these tasks in a many to one relationship (Figure 2-7). However, whilst there are no major ommisions in the IFC schema for the definition of construction schedules, there are currently no commercial applications that have implemented IFCs in this way (buildingSmart 2007, Weise *et al.* 2009a).

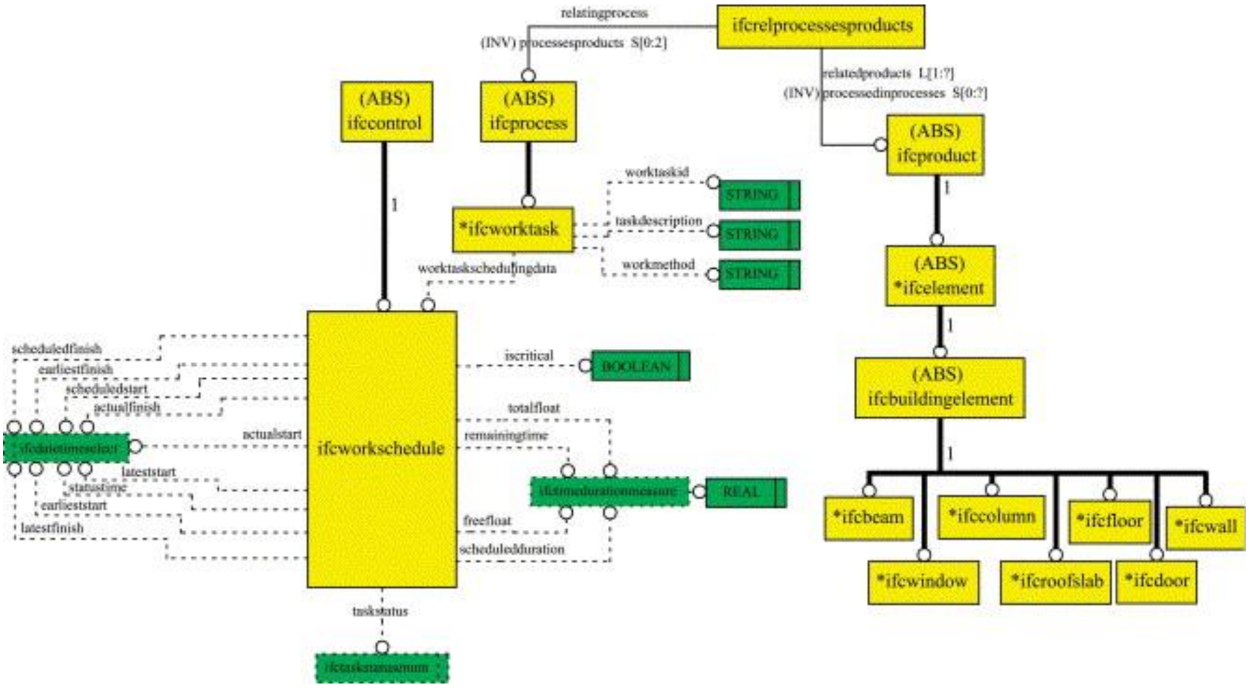


Figure 2-7 Relationship between a Work Task, Work Schedule and the spatial structures and products in IFC (Source: Tanyer and Aouad 2005)

As a salient subject in construction research for many years, BIM and the allied IFC data model have been incorporated into many research efforts into 4D CAD and construction scheduling. Märki *et al.* (2006) used an object-oriented database in their ‘Interactive Toolbox for 4D Modeling’ to store inputted IFC files, while Jongeling and Olofsson (2007) used IFC files to transfer model data from ArchiCAD to AutoCAD Architectural Desktop in their research project into location-based scheduling and 4D CAD. WISPER (Faraj *et al.,* 2000), a proposed Web-based Project Environment seeks to provide integrated design, cost estimation and scheduling within a distributed environment that separates data processing functions from the object-oriented IFC database and the client interface. This implementation of IFC enables object oriented design creation within an AutoCAD environment, web-based visualisation using an IFC-mapped VRML file, estimating where quantities are retrieved directly from the IFC database and planning where work groups are generated directly from the IFC onto which users map task durations and dependences. Further developments during the *n*D modelling initiative at Salford University adopted a single project database approach in an IFC-based tool that sought to add the further dimension of cost to the 4D modelling paradigm (Tanyer and Aouad, 2005).

Many construction research efforts have sought to leverage the objectified, open and interoperable nature of BIM and IFCs to address numerous construction related tasks and problems. An IFC model viewer was developed at Salford University to support their *n*D modelling research efforts and described in a paper reviewing how BIM impacts on ICT implementation within the construction industry (Fu *et al.,* 2006). Using a file-based approach rather than a database model server, this project employs the IFCsvr ActiveX component from VTT research in Finland to parse IFC files and extract the geometric information. Once extracted, the relationships are re-mapped to a hierarchical tree-view representing only the physical entities with the file. These entities are then linked to corresponding VRML geometrical entities that were created using a third party tool, thus allowing object selection to take place graphically or within the tree view. Two further unrelated studies have suggested extensions to the IFC format specification to enable the inclusion of domain-specific information in the fields of data provenance tracking and building lifecycle management (Petrinja *et al.,* 2007; Vanlande *et al.,* 2008). The Rosewood experiment, a study investigating the use of BIM for product model data exchange during the design and fabrication of office block facades, concluded that productivity gains of 57 per cent were made over the traditional 2D CAD-based workflow (Sacks *et al.,* 2010). Research carried out within the scope of the InPro project (InPro, 2010) investigated problems with using an IFC-based model server for data exchange to support collaboration during the early design phase. One such study investigating the performance of different data sharing mechanisms within a BIM-based server-client environment, concluded that the ability of a centralised model server to manage different BIMs, perform queries and create and merge partial models was severely and negatively impacted by data models over 2 megabytes (MB) (Nour, 2009). Other work explored the differing levels of geometry granularity required for design, Quantity Take-Off (QTO) and scheduling and proposes an object splitting algorithm and also a method for capturing this information within the original IFC file whilst maintaining the original model's integrity (Tulke *et al.,* 2008). Further studies performed under the banner of this Europe-wide project propose an IFC model-based scheduling approach which seeks to bring together the fields of architectural design, construction scheduling, quantity take-off and cost management (Weise *et al.,* 2009a; Weise *et al.,* 2009b). The implemented Scheduling Assistant presents rule-based linking and automatic splitting of model geometry based on construction grids or work zones, thus automatically matching granularity between schedule and model, reducing the amount of initial set-work required and enabling easy updating in case of changes to the design; however, they note the lack of IFC support in current cost management and QTO software applications, suggesting this an important area for future development towards full implementation of this novel approach.

The following examples demonstrate IFC usage during recent major construction projects as published by the buildingSMART International Alliance for Interoperability and as such may reveal the level of penetration of BIM within the construction industry:

- The €900 million Akershus University Hospital project in Norway, where complete BIMs were built by the architects and HVAC engineer and were used for quantity take-off and clash detection between the different disciplines.

- Haileybury School in Kazakhstan was designed from the ground up in BIM compliant modelling software which enabled the architect to pass the completed BIM directly onto the main contractor who was using Revit Structure to model the structural steel elements of the building; gaining an ‘Excellent’ rating from the BREEAM environmental assessment scheme.
- 5 Churchill Place on Canary Wharf, London is a 30,000 square metre commercial project during which the architect and main contractor both used versions of Revit to create and share building models of the proposed and existing buildings and incorporate the steel fabrication models from the Dutch contractor.
- The British Embassy project in Jakarta, Indonesia displays an innovative and sustainable design and was developed from the ground up using BIM-compliant Revit Architecture, the resulting BIM was then utilized by the structural engineer within Bentley Structure and by the service engineer in Revit MEP to improve communication and coordination throughout the whole team prior to and throughout the construction (buildingSMART, no date).

Data exchange and software interoperability is, and always has been a difficult yet important undertaking within a construction project (Pazlar and Turk, 2008). Similarly, construction planning is a critical and complex task that must be undertaken to ensure the successful completion of a project (Hendrickson, 2008). Zhou *et al.* (2009) suggest that planning for construction is increasingly being supported by 4D CAD. Projects such as the PM4D project at Helsinki University (HUT-600) (Kam *et al.,* 2003) and the InPro initiative, together with the real world projects cited above, provide evidence that 4D CAD is increasingly being supported by BIM and its product, the IFC data model. Recent research has also highlighted the potential benefits and challenges of leveraging BIM in personalised context aware project management applications for the construction industry (Aziz *et al.,* 2009). However, the semantically rich and relational product model provided by Building Information

Modelling and the IFC should not be seen by itself as the panacea to all the industries problems with interoperability and effective data exchange, as problems with data exchange and interoperability between different IFC-compliant software have been shown to still exist (Pazlar and Turk, 2008).

2.5 SUMMARY

In this chapter a critical review of the current established construction planning approaches, communication tools and industrial practice was undertaken. Following this, an examination of the current state-of-the-art of 4D modelling in construction research and 4D CAD practices and tools was carried out together with an examination of their dissemination into real construction projects. Finally,xz current and emerging research into Building Information Modelling in relation to 4D CAD was explored to provide a solid background onto which this research project can be projected.

The following chapter discusses the technical and practical considerations surrounding the enabling technologies for an on-site BIM centric 4D planning tool.

Chapter 3

3 Enabling Technologies for AR4D

3.1 INTRODUCTION

The previous chapter highlighted both the inherent problems and shortcomings with current construction planning practices and the current and emerging research efforts that have sought to address issues such as miscommunication, ineffective coordination and mental abstraction that have been elucidated in the research. This chapter provides a review of current literature surrounding augmented reality and sets out a discussion around the technological implications and practical considerations of implementing an on-site model-based augmented reality planning tool.

Section 3.2 provides an introductory overview of Augmented Reality (AR). Section 3.3 examines implementation and application of AR within academic research and industrial applications. Section 3.4 considers the technological challenges associated with implementing an AR system, including tracking technologies and image registration. Section 3.5 explores GPS as a positioning technology, its inherent shortcomings and technical challenges and discusses techniques for their mitigation.

3.2 AUGMENTED REALITY

Augmented reality (AR) is an advanced Information Communication Technology (ICT) solution that combines digitally stored and spatially referenced visual, aural or even haptic information with the physically real environment in real time (Azuma, 1997; Azuma *et al.,* 2001; Choi, 2009). AR technology enhances a user's perception and situational awareness through intuitive contextual presentation of information (Behringer, 1999) and has been shown to enable straightforward collaboration, intuitive interaction and integration of digital information within the context of mobile computing (Schnabel *et al.,* 2007). Furthermore, AR provides the tools and technology for creating augmented workspaces in which the user can interact with virtual content within the familiar context of their physical workspace (Wang, 2008b). This section explores AR technology within the context of current and emerging research, applications, and technological issues related to its potential for industrial deployment especially within the construction industry.

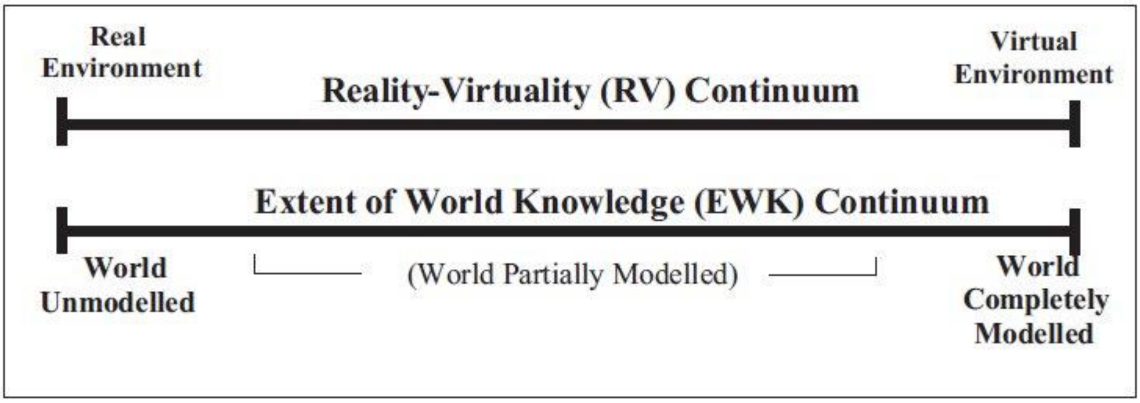


Figure 3-1 Milgrams Continua

AR belongs to a subset of Virtual Reality (VR) technologies known as Mixed Reality (MR), an all-encompassing definition of augmented spaces set out in a seminal taxonomy of computer displays for combining real and virtual worlds (Milgram and Kishino, 1994). This taxonomy does not however define fixed boundaries between the various flavours of MR displays to create separate classifications, but rather defines them by means of their position along the Reality-Virtuality (RV) Continuum, where Real Environments (RE) represent one extremity and purely Virtual Environments the other (Milgram and Kishino, 1994; Milgram and Colquhoun, 1999). This RV continuum, and the various subsets of MR that it describes, are further elucidated by way of its one to one relationship with the parallel Extent of World Knowledge (EWK) continuum (see Figure 3-1). To clarify, the EWK continuum classifies systems according to the extent of the knowledge held by the computer about the world view being presented to the user; therefore a VE is described as a completely modelled environment, i.e. all the information needed to create the world view is held by the computer, where by contrast all the computer is aware of in an RE is the video file or input stream and thus is described as completely un-modelled (Milgram and Colquhoun, 1999; Moloney, 2009). Residing as it does between reality and the middle of the RV continuum, it can be seen that AR will possess imperfect or uncertain information regarding the contents of the Mixed Environment (ME), for instance the geometrical description and geo-reference of a 3D model may be known, whereas the system will typically have no information regarding the real environment into which these virtual augmentations will be merged, other than it is a video stream or file. This situation of incomplete system knowledge means that AR environments can be described as having a partially modelled world view (Schnabel, 2009), moreover Coelho *et al.* (2004) propose that human-computer and human-human interaction within an AR environment is predominantly constrained by the system’s incomplete world knowledge. Augmented Virtuality (AV) is similarly an MR-based technique for combining the real and virtual worlds, however with AV the augmentation is carried out within a predominantly virtual environment, that is to say that reality is viewed from a virtual perspective (Milgram and Colquhoun, 1999). Providing an MR environment that merges a visually rich and layered multi-modal 3D view of the world into a VE, AV is able to deliver a more capacious form of VR, however despite some limited examples, such as Wang (2007), it has never been as popular a research topic as AR, especially in construction related research (Schnabel *et al.*, 2007). All of these new “realities”, or world views, set out within the RV continuum, including the later subdivisions such as mediated or diminished, amplified and virtualized realities (Schnabel *et al.,* 2007; Schnabel, 2009), merge with or replace parts of the user's world view, and thus have the potential to enhance the nature of their interaction with and perception of the physical world (Azuma *et al.,* 2001). Azuma (1997) further defines common properties that all AR systems should possess:

1. Blending the real and the virtual within a real environment.
2. Enabling interaction in real time.
3. Being registered in 3D, where registration refers to the accurate alignment of the real world and the virtual content.

Registration is a fundamental necessity for the successful implementation of AR and as such is a topic for continuing research (Romão *et al.,* 2002; Dunston and Wang, 2005). Azuma (1997) expounds that if the real and virtual worlds are not properly aligned with each other (registered), the illusion of co-existence will dissipate, leaving the user vulnerable to motion sickness due to the disparity of sensory input and the accuracy of the human ocular system. Accurately and continuously monitoring the position and orientation of the users point-of-view (POV) is crucial for successful registration in AR, as it allows the positions of the real and virtual components to be constantly updated in relation to each other (Romão *et al.,* 2002; Behzadan *et al.,* 2008b). To this end tracking systems based on mechanical, magnetic, inertial or optical sensors, marker-based computer vision techniques and combinations thereof have been successfully employed in a variety of construction-related AR systems (Dunston and Wang, 2005). Nevertheless, Azuma *et al.* (2001) postulate that while many approaches to AR in construction have demonstrated robust and accurate registration in use, these have predominantly been in prepared and controlled indoor environments. Deploying AR on a construction site, with its characteristically expansive, uncontrolled and unprepared setting, precludes the use of many of these technologies (Behzadan and Kamat, 2007b), while Dunston and Wang (2005) suggest that the requirement of accurate long-range sensors and trackers is one of the biggest obstacles to successful outdoor site-based AR.

As a subject of continued research since Ivan Sutherland proposed his Ultimate Display over forty years ago (Sutherland, 1965), AR has afforded the research community the potential of a new paradigm for exploring and manipulating objects within 3D space. The augmented or mixed environments that result from the application of AR techniques, provide visualisation and interaction possibilities that are simply not possible in a purely physical environment (Chastine *et al.,* 2007). Schabel *et al.* (2007) explain how through AR, a perceived space containing virtual content is correspondent to the user's action space within the real world. Furthermore the rationale behind the *Studierstube* study (Schmalstieg *et al.,* 2002) was that as a less obtrusive sub-class of VR, AR was better suited to collaborative work applications requiring routine manipulation of 3D information. Nevertheless the opportunity to exploit ARs full potential in this regard has been limited mainly to scientific and research-based visualisation (Kaufmann *et al.,* 2000; Schmalstieg *et al.,* 2002; Schall *et al.,* 2009b), with a great deal of these research efforts to date being concerned with providing the three basic enabling technologies of tracking, display and interaction to an acceptable level of accuracy and usability (Azuma *et al.,* 1999b; Coelho *et al.,* 2004; Reitmayr and Drummond, 2006; Shin and Jang, 2009).

Of the three essential components of AR however, it is convincing and robust registration between the real world and virtual artefacts that has always been the most elusive and challenging problem facing the AR system designer, especially in outdoor environments (Shin and Dunston, 2009). Some research has suggested that, because there is no single perfect tracking solution, application designers typically either just use equipment that is already available to them, or choose the cheapest solution that appears to satisfy their particular systems requirements (Coelho and MacIntyre, 2003). Other work has further suggested that due to the persistence of the registration problem, most examples of AR development to date are either based around a system that needs only limited registration accuracy, or where accuracy is needed, it is often facilitated by the use of artificial means most suited to indoor usage (Dunston *et al.,* 2007).

3.2.1 Indoor AR

Indoor applications of AR, by their very nature, take place within controlled environments defined by the physical boundaries of the space they occupy. That is to say, unlike outdoor AR, physical constraints on a user's movements are created by the predetermined boundaries of an indoor AE, thus simplifying the system model, furthermore tracking a user within a known environment can be further simplified through the use of markers, sensors, cameras or other motion tracking equipment (Behzadan *et al.,* 2008b). Examples of the various approaches employed by researchers towards accurate indoor tracking include mechanical, electromagnetic, optical, wireless networks and infrared. However, as with optical marker-tracking techniques that require constant line-of-sight with calibrated markers placed around the environment, most of these techniques place constraints upon and require some preparation of the physical environment; additionally as with magnetic or ultrasound sensing technologies, many can only operate within a relatively small working area (Behzadan *et al.,* 2008a). Calibrated makers (fiducial), used with computer vision techniques and magnetic sensor tracking were employed to support the use of various tangible user interface devices in a studio-based collaborative urban design experiment (Seichter, 2007), likewise a more recent application of the *Studierstube* collaborative AR framework (Schmalstieg *et al.,* 2002) saw similar marker-based computer vision techniques employed to facilitate the use of tangible AR interaction devices (Billinghurst *et al.,* 2005).

Other researchers have proposed methods for further optimizing the registration method employed in such marker-based computer vision techniques (Yuan *et al.,* 2005) to enable more robust vision tracking within a prepared environment, while the Shared Space project employed the proprietary Polhemous™ magnetic tracking system in their early research into collaborative AR work environments (Billinghurst *et al.,* 1998). A highly accurate commercial optical tracking system that requires arrays of ceiling mounted LED beacons was specified in a novel approach to steel column fixing bolt inspection. This highly precise task is normally performed with a calibrated total station, therefore the authors opted for a highly accurate proprietary approach to attain acceptable levels of accuracy in this lab-based prototype (Shin and Dunston, 2009). Many such examples of AR research have reported acceptable levels of tracking accuracy in use, however many of the techniques used either restrict the size of the AE by way of their limited working range, or require preparation of the environment with markers, beacons or sensors thus preventing their use in an outdoor environment (Behzadan *et al.,* 2008a; Shin and Dunston, 2008).

3.2.2 Outdoor AR

Outdoor AR environments have always presented a much more expansive and chaotic set of technological problems for a system designer to mitigate than its indoor variety. Behzadan *et al.* (2008a) further illuminate that, unlike the controlled nature of an indoor AR environment, a user operating in an outdoor AR setting is presented with no such limitations or prescriptions on their movements around both real and virtual worlds. Early research in this field identified the need for self-sufficiency in power and equipment due to lack of resources in the field, the lack of control the designer or the user have over environmental conditions, and the sheer range of operating conditions encountered in outdoor AR as being the biggest hurdles to its successful implementation (Azuma *et al.,* 1999a), while other studies reported that the search for accurate outdoor tracking constituted an on-going topic for research in the field (Azuma *et al.,* 2001). Later work has reaffirmed that this problem with a lack of suitable technology for outdoor AR is still very much the case (Shin and Dunston, 2008), while Behzadan *et al.* (2008b) clarify four critical requirements for outdoor mobile AR:

1) Accurate registration with minimal user constraints in unprepared environments
2) Robust user interface for augmented environment visualisation
3) Suitable portable power source
4) Backpack mounted equipment to enclose and distribute its weight (Behzadan *et al.,* 2008b)

Technological advances have enabled more accurate outdoor tracking for wide area AR; the field of vision-based tracking has extended the scope of its work into unprepared outdoor environments and is often returning compelling results (Reitmayr and Drummond, 2006; Schall *et al.,* 2009b), similarly new techniques that have improved the reliability and accuracy of GPS have also increased its suitability for real-time positioning applications (Roberts *et al.,* 2002a; Kavanagh, 2003). Despite the persistent issues surrounding its technical implementation, much research has sought to understand, extend and leverage the potential benefits of AR as an outdoor context aware information visualisation system. Early examples of outdoor AR sought to mitigate shortcomings in hardware technology through system design, for example commercial-of-the-shelf (COTS) hardware was used in an early development of a wearable AR system for researching tether-less AR navigation applications. However due to hardware (and software) limitations it only facilitated a limited set of location and context aware visual cues to the user, while the horizon silhouette maps used in the vision tracking system needing to be created *a priori* (off-line) (Behringer *et al.,* 2000). The *Touring Machine* project employed a similar approach to enable the visualisation of interactive geo-referenced labels pertaining to objects within the real world, but noted that usability was impaired by the poor display quality of headsets available at the time, coupled with tracking problems resulting from unreliable or missing GPS readings (Feiner *et al.,* 1997). Later examples of outdoor AR have made good use of advancements in both computing and sensing technologies; Roberts *et al.* (2002) leveraged the sub-metre accuracy of real-time kinematic (RTK) GPS in their visualisation system for underground services and pipes, while a later study has taken advantage of the ever decreasing size of computing hardware by using a camera-equipped handheld computer furnished with a wireless GPS device for interactive outdoor visualisation of as-planned buildings (Honkamaa *et al.,* 2007). Other studies have suggested that the accurate real-time tracking requirements of outdoor AR are not met when using just one technology, requiring instead an approach that combines the strengths of various methods simultaneously to offset shortcomings or weaknesses of individual solutions (Schall *et al.,* 2009b), indeed this so-called sensor fusion approach has been advocated in one form or another by many studies examining outdoor AR over the years (Azuma *et al.,* 1999a; Jiang *et al.,* 2004; Reitmayr and Drummond, 2006; Schall *et al.,* 2009b).

In the following section, a non-exhaustive list of current and emerging AR applications will be examined to gain a broad appreciation of current and emerging application areas. This review will examine AR usage in terms of both scientific and work-task oriented research studies, provide insight into implementation issues faced, and thus facilitate a better understanding of the inherent strengths and weaknesses with each individual approach.

3.3 IMPLEMENTATION OF AR TECHNOLOGY

Many early examples of research into AR systems saw them used as test-beds for system designers to research methods of exploring and exploiting the potential of the new human-computer interaction (HCI) paradigms afforded by this interface between technology and the physical world (Feiner *et al.,* 1997; Billinghurst *et al.,* 1998; Höllerer *et al.,* 1999; Behringer *et* *al.,* 2000). In other studies it was the technicalities of building robust, usable and ultimately accurate AR systems that was explored, such as hardware considerations, software design or emerging tracking technologies (Piekarski *et al.,* 1999; Schmalstieg and Hesina, 2002; Behringer, 1999). Concurrently, others were investigating different approaches to alleviate problems created by technological shortcomings or constraints of current tracking solutions. One study advocated adaptive interface design to mitigate the effect of incomplete tracking data on an indoor AR navigation system (Hollerer *et al.,* 2001), while the use of probabilistic methods for accommodating tracker error (MacIntyre *et al.,* 2002) or signal processing techniques to produce stabilized tracking sensor data (Ribo, 2002) are two examples of how advanced mathematics and engineering methods have been applied to an AR system design problem to provide improvements through software design.

3.3.1 Research based AR systems

Due in part to the limitations imposed by the level of functionality in supporting technologies, many early developments of AR systems were predominantly indoor applications, especially when precision and accuracy are concerned such as in mechanical CAD based visualisations (Dunston *et al.,* 2000). However, some studies also investigated architectures and applications of outdoor AR. One early and influential example was developed by Azuma *et al.* (1999a) which investigated the development of motion stabilized tacking in outdoor AR. Focusing on the software and hardware issues faced in outdoor registration, they propose the use of multiple orientation sensors to offset the weaknesses of each individual solution. Their sensor fusion approach successfully used an advanced filtering and estimation technique called the Kalman filter to allow the angular position and rotational rate of the user's head to be estimated from the combined input of a compass and a three axes gyroscope. The combined and filtered data is then projected forward one frame into the future to offset system lag resulting from sensor latency and the filtering process itself (Azuma *et al.,* 1999a).

Work undertaken at the Wearable Computer Lab, University of South Australia, saw similar development of hardware and software configurations for outdoor AR that has continued to develop over the last 12 years. Based around a bespoke wearable AR computer system that in its current incarnation uses differentially corrected GPS for location, the proprietary InertiaCube 3™ from InterSense for gaze direction together with a set of custom “pinch gloves” with marker tracked thumbs for GUI manipulation and cursor control respectively (Thomas, 2009). Applications of AR from this project have covered outdoor architectural visualisation (Thomas *et al.,* 1999), an AR-enabled version of the well-known “Quake” gaming environment (Thomas *et al.,* 2002), an innovative system for in-place 3D modelling in an urban environment, including novel mechanisms for hands-free HCI and virtual content creation and control (Piekarski and Thomas, 2002) and an attempt to extend the application of AR with see-through vision to allow the visualisation of objects occluded by buildings (Avery *et al.,* 2008). However, rather than being developed as to address particular real-world problems or needs, the tasks around which these studies or the problems serve mainly as a conceptual framework, around which the hardware and software infrastructures that supports the Tinmith wearable AR system and the glove-based interaction mechanism, TinmithHand, are continually developed. A technical review of all work carried out under the auspices of the Tinmith project is beyond the scope of this work, however a detailed review of all of the project research to-date can be found in Avery *et al.* (2010).

Figure 3-2 The Tinmith Wearable AR System (Avery et al., 2010)

Since 1996, a research project investigating the application of AR for collaborative and ubiquitous computing has seen the development of the Studierstube software framework for creating collaborative VR and AR applications (Kaufmann *et al.,* 2000; Schmalstieg *et al.,* 2002). Using orientation-tracked optical see-through Head Mounted Displays (HMD) to enable collocated users to interact with each other and a shared 3D visualisation, together with the development of a Personal Interaction Panel (PIP) tangible control device which is visually augmented with application-specific controls, the Studierstube project was one of the first AR systems to provide ground-up support for collaborative working within a shared AR environment (Schmalstieg *et al.,* 2002; Szalavári and Gervautz, 1997). Focusing predominantly on the technical challenges facing the development of collaborative AR environments (Schmalstieg and Hesina, 2002), examples of application areas to which this framework has been applied include Construct3D, an educational tool for mathematics and geometry using a virtual geometry construction paradigm (Kaufmann *et al.,* 2000; Kaufmann, 2002) and indoor navigation and path finding using fiduciary markers and vision-based tracking (Kalkusch *et al.,* 2002). Other work saw Studierstube being extended and applied to outdoor environments, such as a collaborative outdoor AR for navigation within a mobile tourist guide-based application (Reitmayr and Schmalstieg, 2004) in which users can view location-specific information regarding buildings or places of interest and leave their own geo-referenced tags for others to view. Recent studies have seen the development and optimization of techniques for implementing Studierstube-based AR applications on handheld mobile devices and smartphones, for example optimized maker-based and natural feature tracking techniques (Wagner *et al.,* 2008; Wagner, 2009).

Many researchers have also sought to provide robust tracking and registration in outdoor AR applications. Work undertaken at the Graz University in Austria saw the development of a test-bed system for the development of hybrid tracking for robust outdoor AR (Ribo, 2002). The developed wearable AR system uses computer vision techniques to estimate, identify and track corner features across each frame of the video stream and return a 6DOF (rotation and position) pose estimation; this result is then fused with the 6DOF output from the accelerometer and gyroscope based Inertial Measuring Unit (IMU) by means of an extended Kalman filter algorithm to produce stable registration at near real-time frame rates (Ribo, 2002). Tenmoku *et al.* (2003) proposed a wearble test bed AR navigation system that uses RFID tags and InfraRed markers to form an indoor-outdoor positioning infrastructure with a dead-reckoning pedometer providing a backup solution when the user is out of its range (Tenmoku *et al.,* 2003). However, an issue with such an infrastructure centred approach is predominantly the working range afforded the user, while the work involved in preparing the environment prevents its use in many real world situations.

A later example that builds upon and extends previous work into hybrid tracking techniques and mobile outdoor AR, “Going out” (Reitmayr and Drummond, 2006) combines a handheld computer and 3DOF orientation sensor with a model-based visual tracking approach to provide accurate and robust registration. The visual tracking module works on salient edges which are extracted from geometrically optimized, geo-referenced, photorealistic 3D models generated off-line and pre-loaded into the system. Loss of registration resulting from transient occlusion of visually tracked features is an inherent problem with visual tracking techniques (Reitmayr and Drummond, 2006). However, by using the last successfully tracked video frame from a buffer with the corresponding camera pose information, recovery can be attempted based upon the assumption that visual tracking will be able to restart within a few frames. In use, this system provides compelling and robust registration, however while its ability to recover from losses of registration due to occlusion proved to be robust within a visually simple environment, there was a reported trade-off between scene complexity and the robustness of the recovery system. Of note here is that unlike the previous approach where tracking is able to occur within an unknown environment, or others where environment maps are created in real time from the video feed (Schall *et al.,* 2009b), this tracking system calls for the a priori creation of photo-textured 3D models of the environment to be used. Such potentially expansive model engineering tasks are time and therefore cost and resource consuming (Behzadan and Kamat, 2005), although others have advocated surveying techniques such as radar, ultrasound, GPS driven laser pointers, GIS systems or 3D laser scanning as being potentially suitable technologies for reducing the time spent on creating and re-engineering these so-called reality models (Klinker *et al.,* 2001; Wang, 2008a).

3.3.2 AR based Work

Scientific and lab-based research efforts have continued to push back the boundaries of what is technically possible with AR as a medium for information visualisation and communication; however successful application of these techniques to real world tasks and problems will enable the development of novel support tools that engender task-centred communication and collaboration, and through contextual information delivery can enhance productivity at work.

AR can be seen to fill the gap between the real world and virtual worlds by overlaying and correlating an observed view of reality with virtual elements, objects or information. This insertion of virtual space into physical space enables the data visualisation capabilities of VR to be accessible from the real world, thus assisting with the task in hand through the creation of data rich augmented workspaces (Webster, 1996; Klinker *et al.,* 2001; Dunston and Wang, 2005; Dunston and Shin, 2009). From an experimental study into the use of AR during architectural design, Seichter (2009) concluded that it should be viewed as a complete communication medium, rather than a mere tool for visualisation. By facilitating the contextual delivery of information to the user, AR presents opportunities for the investigation of intuitive work-oriented human-computer interaction that will expedite improvements in decision making across all personnel within a project (Dunston *et al.,* 2007). In concurrence, a sizable body of evidence supports the notion that AR has the potential to improve task and project performance within the construction industry, e.g. (Dias *et al.,* 2003; Shin and Dunston, 2008; Dunston and Wang, 2011). However a major obstacle to its successful implementation therein is still the dichotomy between the required accuracy of the spatial information regarding the location and orientation of the user, and the limitations of the hardware and software techniques employed for the purpose (Shin and Dunston, 2008).

3.3.2.1 Indoor Work

AR has been specified in numerous studies relating to industrial maintenance, planning or training over the years. One early study proposed an immersive AR system as a visual demonstrator / training tool that utilized a HMD and marker-based tracking for guiding a user through the task of assembling and fitting the lock to a car door during manufacturing (Reiners *et al.,* 1999). A further comparative study provides experimental evidence to ratify how the use of AR can improve task performance whilst relieving the mental workload associated with product assembly (Tang *et al.,* 2003). Comparing spatially referenced AR-based Computer Assisted Instruction (CAI), non-spatial HMD and screen delivered CAI and printed manuals, the authors found that despite limitations with camera calibration, tracking and display technologies, the results of their experiment indicates that instructional AR reduced mental effort, negated cumulative errors and reduced actual assembly errors by 82% (Tang *et al.,* 2003). Running from 1999 to 2003, the ARKIVA project (Weidenhausen *et al.,* 2003) explored the use of AR within an industrial setting to support mobile maintenance work; however despite identifying numerous industrial scenarios that would benefit from AR, technological problems relating to the implemented optical tracking algorithms were acknowledged together with practical issues relating to HMD use.

Further work has seen the development of a prototype AR tool for visual manufacturing planning (Doil *et al.,* 2003). This table-top planning tool enabled personnel to visualise and interact with virtual planning objects and relevant documentation during the planning process and despite cited shortcomings with display and tracking technologies was shown to both reduce costs and improve the quality of data that was captured throughout this process. A later study completed under the auspices of a project examining methods for increasing worker productivity in engineering and maintenance, showed that leveraging existing design and maintenance data provided a cost-effective method for developing an AR tool for plant lifecycle management (Siltanen *et al.,* 2007). While others have proposed an optically-tracked simulation-driven MR application as a cost-effective factory layout planning tool (Lee *et al.,* 2011).

During the early design stages of a construction project, designers explore and generate new form combinations which they invariably represent and communicate through sketches (Goldschmidt, 1994). Sketchand+ is an experimental tool that seeks to embody this rapid and fuzzy expression of the early design phase within an AR environment (Seichter, 2003). Using marker-based tracking and NURBS (Non-Uniform Rational B-Splines) technology to facilitate the creation of 3D forms, this desk-based application demonstrated the potential of this approach despite the usability and technological issues associated with the development of such an experimental tool. BenchWorks (Seichter, 2004) is a test bed AR system developed to examine different interaction techniques to support collaboration within the context of urban design. A successor to sketchand+, and inheriting many of its modelling and interaction techniques, this system employs HMDs with orientation tracking, tangible interaction devices and an interactive table top surface to facilitate the development and exploration of 3D urban massing models, and in this form has gone on to be the base system for a number of further studies into such areas as tangible user interfaces (Seichter,

2007) and communication patterns and behaviours (Seichter, 2009) within a collaborative studio-based AR urban design context.

A further example of AR being used for design purposes is ARCAD (Dunston *et al.* 2002), an interface for table top AR-based visualisation and exploration of mechanical piping systems. Visually tracked markers are utilized for physical manipulation of a 3D virtual model whilst the augmented scene is viewed through a HMD. Originally cited as a system for exploring the potential benefits of AR in the design process, later work concludes that when comparing the level of spatial cognition afforded the user over the standard CAD view, this prototype tool reduced the amount of time spent on conflict detection by 71% (Wang and Dunston, 2006). Further work has seen the proposition of a conceptual AR system for site layout and logistical planning (Wang, 2008b). Using marker based visual tracking, tangible user input devices and HMDs, this table top prototype planning tool provides a rule-based decision support environment for collaborative construction site planning. Shin and Dunston (2009) have further proposed a novel approach that uses AR in a prototype structural steel column inspection tool. The prototype ARCAM system is presented as an easily set up alternative to the conventional total station approach. However, despite showing potential for future development, the use of a proprietary indoor tracking system was necessary to gain acceptable levels of accuracy, and thus prohibits its use in an outdoor environment in its current form.

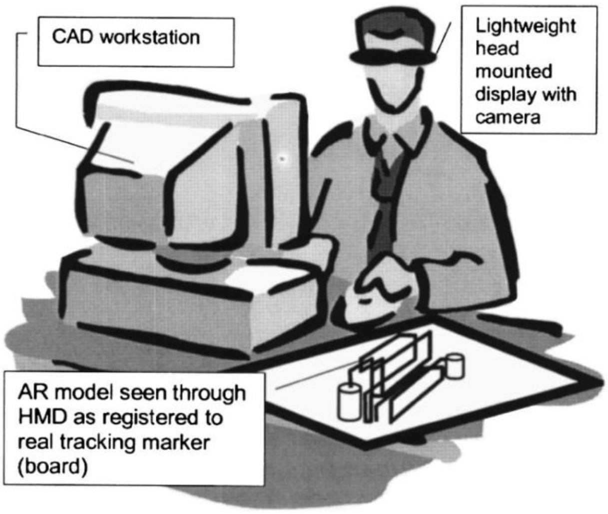


Figure 3-3 The ARCAD System (Dunston et al., 2002)

3.3.2.2 Outdoor Work

The above examples demonstrate the feasibility of utilizing indoor AR as a test bed for work task investigation or enhancement. Conversely, building upon and extending the scope of others' work into outdoor systems, some studies have attempted to leverage AR within the context of outdoor work task execution or enhancement; yet there are still very limited examples of its actual use in the field to support everyday working practices.

Whilst not a system intended for work enhancement, the ARCHEOGUIDE system (Gleue and Daphne, 2001; Vlahakis *et al.,* 2002a) is an on-site mobile AR archaeological information system designed for use by visitors to archaeologically interesting cultural heritage sites. Built using COTS hardware, this augmented tourist guide application combines DGPS and a 3DOF compass module with vision tracking techniques based on template matching, to provide robust outdoor tracking that enables the enhancement of the visitors experience with contextual audio-visual information, including virtual 3D monument reconstructions, audio narration, site navigation and avatar-populated virtual historical re-enactments (Vlahakis *et al.,* 2002b). Nevertheless, constraints placed on this application result in it not being a true free-roaming AR system, specifically the template matching algorithm and therefore the visual tracking routine requires predefined and calibrated images of the surrounding environment. Similarly, the thin-client version, whilst allowing the system to be run on handheld devices, provides only a stripped-down graphical augmentation feature, based on pre-rendered scenes at specific locations streamed from the server.

Imposing constraints upon the physical scope of an outdoor AR system is a suitable approach if the real environment to be augmented is predefined and unlikely to change, however most outdoor work-centric AR systems need to operate untethered within an unprepared environment. Some researchers have proposed such an outdoor AR system that incorporates a spatially referenced database for use in the field of environmental management (Romão *et al.,* 2002; Romão *et al.,* 2004). The developed ANTS system comprises of a video see-through HMD and camera, GPS and a COTS head tracking unit implemented around a modular client-server system. Sharing many of the features afforded by desk-based Geographical Information Systems (GIS) and making them available within AR, the ANTS infrastructure is envisaged as a tool for the delivery of contextual geo-referenced information to provide the worker with intuitive visualisation of complex spatial data, such as visualising a pollutant transport model for a particular body of water (Romão *et al.,* 2002). Later work has sought to further integrate GIS and location-based mobile computing to provide a field operative with the facility to access and manipulate geo-referenced data from various sources, including satellite and airborne photographs, GIS maps or geo-referenced 3D models from within an outdoor mixed reality environment (Lopes and Dias, 2006).

Roberts *et al.* (2002a) inform that while maps of subsurface assets held by utility companies provide essential information for performing maintenance, planning or surveying work, they are often unreliable in accuracy and cumbersome and difficult in use. Therefore they propose an untethered outdoor AR system for contextually visualising geo-referenced sub-surface data. Using sub-metre accurate RTK GPS and a tilt-compensated compass module, the authors attempt to address the problem of unreliable data in the field through accurate and contextual visualisation of subsurface assets and service conduits. A feature of this approach is its use of a handheld display unit which acts as ‘Virtual Binoculars’ through which the user can view the augmented scene, this has the benefit of negating the effects of discomfort and motion sickness often associated with HMD-based AR systems.

Later work into mobile AR for the visualisation of subsurface infrastructure has been carried out under the Smart Vidente project (Vidente, 2010). Implemented using the Studierstube AR framework, an initial development used a purpose built handheld device, Vesp’R, based around an ultra-mobile PC incorporating GPS, orientation sensor and camera (Schall *et al.,* 2009a; Schall, 2009); however issues with standard GPS accuracy, especially within ‘urban canyons’, and difficulty with display visibility in direct sunlight have led to further developments using a rugged tablet PC with a sunlight viewable touch screen and incorporating a visual tracking module to supplement and improve registration in the field (Vidente, 2010).

GPS guidance systems have long been used to assist tractor drivers to perform agricultural tasks in the field; however this conventional approach requires the driver to combine the provided positional information with work maps and field layouts mentally. To assist the driver with this considerable mental task, researchers have proposed a GPS-based AR guidance system that provides a more intuitive method of monitoring agricultural work in the field by providing an overlay of areas to be worked and virtual guidance markers onto the drivers view of the world through a HMD (Santana-Fernández *et al.,* 2010). Building upon interactive screen-based guidance systems already deployed within the agricultural industry, the proposed system allows the monitoring of work progress from inside and outside of the tractor cab by utilizing either a vehicle mounted camera and GPS unit, or through a wearable GPS-based AR system with a camera mounted on the HMD.

The UM-AR-GPS-ROVER (ROVER) is a prototype outdoor AR platform employing a modular software approach to provide registration of geo-referenced CAD models and animations of construction operations in an unprepared environment (Behzadan and Kamat, 2005; Behzadan and Kamat, 2006; Behzadan and Kamat, 2007b; Behzadan *et al.* 2008b). Using GPS and a HMD mounted 3DOF orientation tracker for registration of the CAD objects, together with a wrist mounted keyboard and touch pad for interaction with the backpack mounted laptop computer, the ROVER system employs a ‘reusable and pluggable’ framework that is not tied to specific software modules or hardware devices, thus allowing them to be upgraded as technology advances (Behzadan *et al.,* 2008b). Later studies build upon earlier work into the simulation and visualisation of construction operations in VR (Kamat and Martinez, 2001; Kamat and Martinez, 2002) by employing ARVISCOPE (Behzadan, 2008), a purpose written AR animation authoring language which allows animations of construction activities to be created on-the-fly from the results of DES models of construction activities (Behzadan and Kamat, 2007a; Behzadan and Kamat, 2009). More recent work presented SMART, an AR software application framework and ARMOR, a mobile modular hardware platform, which represents an updated and improved version of the ROVER and ARVISCOPE setup (Dong and Kamat, 2010). Leveraging improvements in hardware technology and incorporating a similarly reusable modular framework to the ROVER platform, ARMOR extends and upgrades the original hardware and software configuration with centimetre-accurate RTK-GPS, advanced filtering and latency compensation algorithms for the orientation tracker, an improved video camera and HMD and a lightweight and more powerful Netbook computer, while the keyboard and touchpad combination are replaced with the ubiquitous Wiimote from Nintendo for user-system interaction.

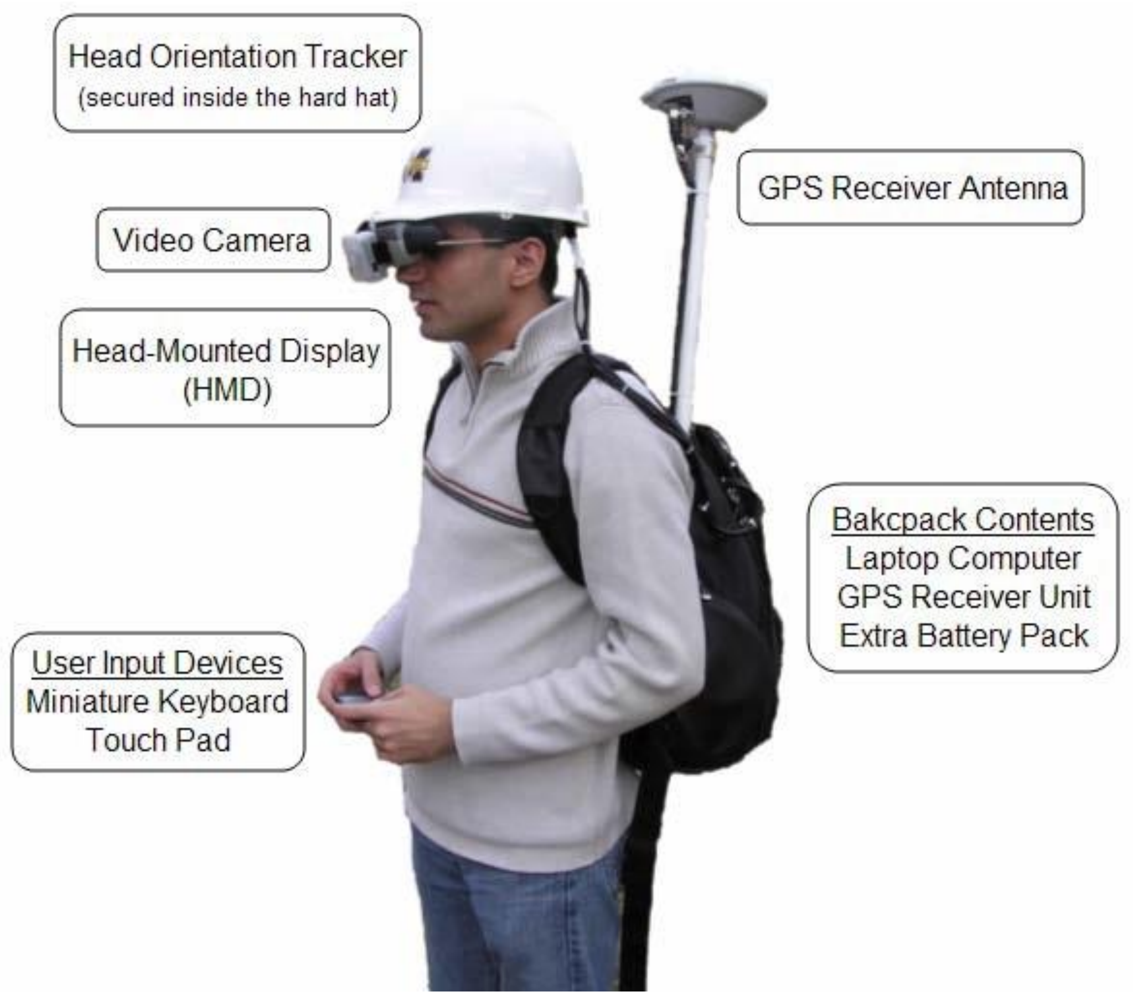


Figure 3-4 The UM-AR-GPS ROVER prototype. (Behzadan and Kamat, 2005)

Work is on-going at the VTT Technical Research Centre in Finland which originated in the development of various VR visualisation applications, including mobile AR, which were implemented during the design, planning and later evaluation of their new head office building in Espoo, Finland (Woodward *et al.,* 2007). Honkamaa *et al.* (2007) describe a mobile AR visualisation solution built around an mini PC using Google Earth for model geo-location, GPS for positioning and a vision based tracker for view orientation. Issues with the Google Earth workflow were cited, as was the need to manually align the view upon initialisation and after moving around the VE as the optical tracker is not able to provide a physical heading and assumes purely rotational movement. A later iteration of this system which is based upon OpenSceneGraph (OSG) is described in Hakkarainen *et al.* (2009) and extends upon the previous system by enabling interaction with BIM-based IFC files and schedule information to provide on-site AR based 4D visualisation of the construction process. First and foremost, a system for architectural visualisation and still in active development, this AR4BC system utilizes the Google Earth API to capture a BIMs geographical position, calculates the sun's position from the GPS information and renders it with ambient light and shadow maps to produce augmented photorealistic visualisation. Future developments into real time ambient occlusion, soft shadows and advanced camera shaders to simulate real world lighting and filming conditions (Woodward *et al.,* 2010) are set to further extend the photorealistic nature of this project's visualisations.

3.3.3 Collaboration in AR

Since the idea of Computer Supported Collaborative Work (CSCW) was first proposed over twenty years ago, many research papers have been published and computer systems developed that incorporate its principles to facilitating person-to-person, work-oriented, real-time communication (Billinghurst *et al.,* 1998; Billinghurst and Kato, 2002; Jiang *et al.,* 2005; Zhou *et al.,* 2007). Communication in the context of unmediated face-to-face collaboration is driven not only by speech and conversation, but also by the use and observation of gesture, gaze and other non-verbal communication cues (Billinghurst and Kato, 2002). However, when collaborators are geographically separated, this non-verbal communication channel must be provided through computer-mediated means (Chastine *et al.,* 2007). In this regard, it has been suggested that to facilitate effective collaboration, the encompassing AR environment needs to nurture a sense of presence between all users as well as provide transparent mechanisms for discussing and sharing data and ideas in real time (Muramoto *et al.,* 2007). Some researchers have elucidated that unlike immersion, which describes an objective physical state afforded by the system’s technology, such as display technologies and interaction modalities, presence is a subjective mental state that describes a user’s psychological reaction to this immersive state and as such can only be assessed by subjective methods, such as post use questionnaires (Nash *et al.* 2000). Conversely, while experimental evidence presented by Wang and Kim (2009) proposes that presence within a virtual environment has only a limited effect on design performance, they conclude that more comfortable and higher resolution HMDs and more accurate tracking may have led to an improved user experience and therefore a different outcome.

An experimental study into communication behaviours in collaborative AR concluded that being able to see both the real world and fellow collaborators during AR sessions made for more natural patterns of communication (Kiyokawa *et al.,* 2002). Billinghurst and Kato (2002) further explain how both the physical environment and tangible objects within it support collaboration during spatially referenced work activities, such as design and planning, by providing, for example, a reference frame for task-centred communication. Chastine *et al.* (2007) concur that enabling AR users to generate their own references within the AE is a critical factor for the success of collaborative environments. They also acknowledge the difficulties encountered in creating effective interaction metaphors for collaborative VEs, noting however that when collaborating in AR, a user will need system features that support communication and mutual awareness between participants, while further recommending the facilitation of methods for pointing or indicating at both real and virtual content (Chastine *et al.* 2007). Azuma *et al.* (2001) explain how by retaining reference to its surroundings, AR naturally lends itself to collaborative working, furthermore they suggest that activities such as design and visualisation will especially benefit from ARs ability to enable all participants to simultaneously view, discuss and interact with a common 3D virtual model from their own point of view. One study proposes thirteen important features that should be incorporated into a groupware application to enhance its usability, including: Standard collaboration features such as text chat, audio and video conferencing, shared information access, presence awareness and support for privacy and security; satisfactory system performance; persistence; reliability; modular and pluggable design; ease of learning and ease of use (Tomek and Giles, 2008). However, they further elucidate that while much research into groupware has mostly overlooked web-enabled devices, work into AR has, to-date, predominantly overlooked real support for collaboration.

By incorporating features of natural communication, such as eye contact and body language, whilst also capitalizing on the benefits of a data-rich virtual world, AR presents itself as a very suitable medium for collaborative work activities such as construction planning. Construction planning tasks entail predominantly mental activities that already spans real and virtual space, thus reinforcing its suitability for use in AR (Schnabel *et al.,* 2007). To illustrate this point further, planning activities require individuals to mentally reflect upon, extract meaning from and modify virtual objects that represent physical components and relationships that do not yet exist, the so-called mental 4D model (McKinney and Fischer, 1998). Correspondingly AR technology facilitates the merging of the real and virtual worlds by overlaying a user’s visual perspective of their real world environment with contextual objects or data. This relationship between the needs of the planning process (task) and the inherent facilities and capabilities of AR (technology) can be better understood, in terms of information systems research, as a potentially good Task Technology Fit (TTF), where tasks represent actions that turn inputs into outputs, technology symbolizes any tool used by an individual to carry out their tasks and the fit between them describes the correlation between the task requirements, the individual’s abilities and the functionalities afforded by the technological solution (Goodhue and Thompson, 1995; Goodhue, 1995). In a study centred around a detailed assessment of construction work tasks a comprehensive map of suitable application areas for AR in construction utilizing the theory of TTF was presented (Shin and Dunston, 2008). Through the identification and assessment of seventeen classified construction work tasks, further categorized as either physical or informational, the authors identified eight tasks that show potential for enhancement through integration with AR. However while scheduling itself does not feature in their complete list of identified tasks, four of the chosen eight which are categorized as informational tasks, namely coordination, supervision, commenting and strategizing, share many of their working processes and needs with collaborative construction planning, such as mental extrapolation of spatial information from CAD drawings, plans and other documentation, and collaboration and the need for natural communication channels between participants including non-verbal cues (Shin and Dunston, 2008).

3.4 TECHNOLOGICAL CHALLENGES OF AR

Previous sections have elucidated and discussed a number of the salient academic studies and industrial applications of outdoor AR technology. It has been proposed that a growing number of these demonstrate the feasibility and potential for AR within the construction industry, while previous work has reinforced the need to address fundamental issues with accuracy and robustness in enabling technologies, to facilitate the widespread adoption of AR by the construction industry (Azuma *et al.,* 2001; Behzadan and Kamat, 2007b; Shin and Dunston, 2008). To concur, Wang (2008a) proposed that technical limitations in current technology is what places the greatest constraints on current AR systems. Indeed the requirement for accurate long range sensors and trackers and the need for efficient calibration methods to integrate them is cited as being the biggest obstacle to the successful implementation of AR on construction sites (Shin *et al.,* 2007).

3.4.1 Tracking and Registration

Tracking the user’s body position and head orientation provides the data necessary for describing their movements around and view of the physical environment. Therefore, by utilizing or transforming to the same coordinate frame within the virtual world that the user physically inhabits, this same data can also describe their movement around an AE. Tracking technologies can be used to monitor the movement of any object or part of the body such as the hands or handheld interaction devices, however typically it will be used to capture the position and rotation (gaze direction) of the head in six degrees of freedom (DOF), namely the x, y and z (latitude, longitude and altitude) of position and the corresponding yaw, roll and pitch rotations of head. These two distinct data sets (position and rotation) are sent from the tracking sensors to the computer at discrete time intervals where they are mapped in real time onto the transformation matrix of the viewing frustum, or virtual camera, to produce alignment between the real and virtual camera. Furthermore, by applying the inverse of the camera’s transformation matrix to the spatially referenced virtual artefacts to be visualised, the tracking data also enables the AR system to keep them fixed within 3D space and thus remain correctly registered within the user’s view of the world (Azuma *et al.,* 2001; Behzadan and Kamat, 2005; Wang and Dunston, 2007; Wang *et al.,* 2013).

Figure 3-5 The 6DOF tracking frame of reference (Behzadan and Kamat, 2005)

Outdoor AR requires tracking technologies that can operate within an unprepared and often uncontrolled environment to provide accurate and robust registration between the real and virtual world, while placing minimal constraints upon the user's movement (Dunston and Wang, 2005; Behzadan *et al.,* 2008b). Wireless signal tracking techniques that use Wireless Local Area Networks (WLAN), Radio Frequency IDentification (RFID) or Infra-red (IrDA) technologies have been deployed for position tracking and localisation within some studies into mobile AR (Tenmoku *et al.,* 2003; Behzadan *et al.,* 2008a), while other studies have explored marker-based optical tracking (Thomas *et al.,* 2002; Kamat and El-Tawil, 2007) or hybrid tracking using visible beacons (Azuma *et al.,* 2006) in an outdoor AR context. Typically with all of these techniques however, the position of the user is calculated based upon either line of sight or the strength of signal received by the user's system from pre-installed beacons, markers or transmitters that are installed at known locations around the real environment. This need to prepare the environment impedes the use of such technologies in many outdoor AR developments, especially those designed for use on construction sites, where the dynamic and constantly evolving nature of the site precludes the installation of such tracking equipment infrastructure (Behzadan *et al.,* 2008a).

The Global Positioning System (GPS) is a satellite-based radio navigation system that measures the time delays of messages sent from in-view satellites to provide continuous global position tracking while at least four of the twenty four GPS satellites have a clear line of sight to the receiver on the ground (Farrell and Barth, 1998; Hammad, 2009). Therefore, to achieve the truly mobile and unconstrained position tracking and view registration that is required by outdoor AR, it has been proposed that GPS stands out as the best current solution (Schall *et al.,* 2009b). Moreover, despite well-known problems such as variable positional accuracy and signal deterioration in covered or built-up environments (Rizos, 2005; Schall *et al.,* 2009b), it has been postulated that as the majority of construction activities take place in an outdoor environment with a clear view of the sky, GPS presents a very suitable tracking solution for AR in construction (Behzadan *et al.,* 2008a). Indeed, the sizable body of work into outdoor AR that has successfully deployed GPS or one of its more accurate variants, DGPS or RTK-GPS, for position tracking, e.g. (Feiner *et al.,* 1997; Piekarski *et al.,* 1999; Roberts *et al.,* 2002a; Romão *et al.,* 2002; Thomas *et al.,* 2002; Vlahakis *et al.,* 2002a; Reitmayr and Schmalstieg, 2004; Behzadan and Kamat, 2007b; Honkamaa *et al.,* 2007; Dong and Kamat, 2010) validates the assertion that GPS presents itself as a viable solution for unconstrained and ad hoc tracking in outdoor AR (Avery *et al.,* 2010).

As previously discussed, accurate registration in AR refers to the proper alignment of virtual content within the real world view. Moreover this problem requires knowledge of both the position and head orientation of the mobile AR user. GPS has been shown to be a viable solution for position tracking outdoors that provides a 3DOF measurement in the form of longitude, latitude and altitude. However, as it does not directly measure orientation a further solution is required for obtaining the additional 3DOF of heading information (Azuma *et al.,* 1999b; Roberts *et al.,* 2002a). Other solutions have been leveraged for tracking the motion of an AR user within an unprepared outdoor environment, including marker free vision-based tracking, while both COTS and custom built inertial sensors, electronic compasses and gyroscopes have extensively been used either individually or in combinations to track the rotational movement and therefore gaze direction of a user's head (Azuma *et al.,* 1999b; Höllerer *et al.,* 1999; Jiang *et al.,* 2004; Schall *et al.,* 2009a).

INertial Sensors (INS) and compass modules measure linear acceleration, rotational rates and heading information respectively, through the application of the physical laws of nature, namely gravity and the earth's magnetic field, and as such do not rely on any kind of preinstalled infrastructure or markers within the environment (Farrell and Barth, 1998). Nevertheless, each of these techniques presents its own set of issues for successful implementation in an outdoor AR system. INS units typically integrate the outputs from a gyro and accelerometer to yield the physical orientation of the sensor, however whilst able to handle rapid movements they suffer from both linear and non-linear drift that accumulates over time. Conversely, modern electronic tilt-compensated compasses are reasonably accurate in use, with typical granularity of around 0.5 degrees, however they are adversely affected by magnetic distortions caused by environmental conditions or proximity to metallic structures or equipment, calling for the use of calibration routines or physical shielding of the device to lessen the effect of these environmental factors (Hammad *et al.,* 2004; Hakkarainen *et al.,* 2009; Avery *et al.,* 2010; OST, 2011). Image processing techniques have been employed for vision-based tracking solutions based upon the identification and subsequent tracking of salient features through the frames of a video stream (Sá *et al.,* 2007). Some of these visual tracking solutions are able to deduce the full 6DOF position and pose of the camera from the motion of the tracked points within the video stream (Ribo, 2002; Reitmayr and Drummond, 2006). However, vision-based tracking alone is characteristically brittle and only able to handle relatively slow movement of the camera due to the effects of motion blur on the video image, whilst being particularly susceptible to other environmental conditions such as variable lighting and transient occlusion of tracked features. In mitigation of these shortcomings, many studies have advocated the use of statistical mathematical methods such as the Kalman filer for combining visual tracking techniques with physical orientation trackers to provide a more robust hybrid approach that is less susceptible to the weaknesses of each individual solution (Ribo, 2002; Honkamaa *et al.,* 2007; Bleser and Stricker, 2009; Schall *et al.,* 2009b).

3.4.2 Occlusion

Accurate registration between real and virtual objects is very important for creating compelling realistic augmented environments (AE), similarly managing occlusions between the real and virtual world is essential for maintaining compelling and realistic visual augmentations (Fischer *et al.,* 2003). Without mechanisms for correctly handling occlusion within the AE, the virtual artefacts will always be drawn over the top of objects in the real world, leading to the user's perception of the augmented space and their presence within it being severely impaired (Sá *et al.,* 2007; Wang, 2008a). Klinker *et al.* (2001) note that correct and convincing registration between virtual artefacts and the real scene the AR system needs a geometrically accurate description of the existing physical environment. This so-called 'reality model' enables the AR system to correctly handle occlusions, enables and validates optical camera calibration and enforces physically accurate constraints upon the interactions between the real and virtual objects. However, as they need to exhibit geometric and geo-spatial accuracy to perform correctly, constructing the reality model itself can be a complex and time consuming undertaking.

One method for capturing a 3D model of an existing scene, the so-called geometry-based approach, involves the use of existing CAD drawings or models that can be employed in conjunction with digital maps or GIS systems to enable the construction of a geo-referenced model of reality (Klinker *et al.,* 2001; Wang, 2008a). However, CAD data is not purposed for this type of usage and is often too large and complex for the AR systems to handle in real time, thus requiring considerable model rework to be carried out manually (Sá *et al.,* 2007). Furthermore Klinker *et al.* (2001) reveal that problems with incomplete scene data and inconsistencies with the Level Of Detail (LOD) found in commercial CAD models means that often a different approach to scene geometry capture is required. Alternative approaches such as radar, theodolites, GPS-enabled laser pointers, GIS systems and 3D laser scanners can be used to capture up-to-date and accurate 3D data of a real environment (Klinker *et al.,* 2001; Wang, 2008a), while computer vision techniques utilizing stereopsis and structure from motion (Bolles *et al.,* 1987) have been used to enable an image-based approach to geometric scene reconstruction (Sá *et al.,* 2007).

In use, the reality model is treated as a ‘ghost’ object by the AR system that represents the existing real environment, in so far as they are not visible in the final rendered composite image. Instead they are only rendered within the depth buffer of the graphics pipeline enabling the computer to use them to visually occlude virtual objects as they would in the real world (Sá *et al.,* 2007).

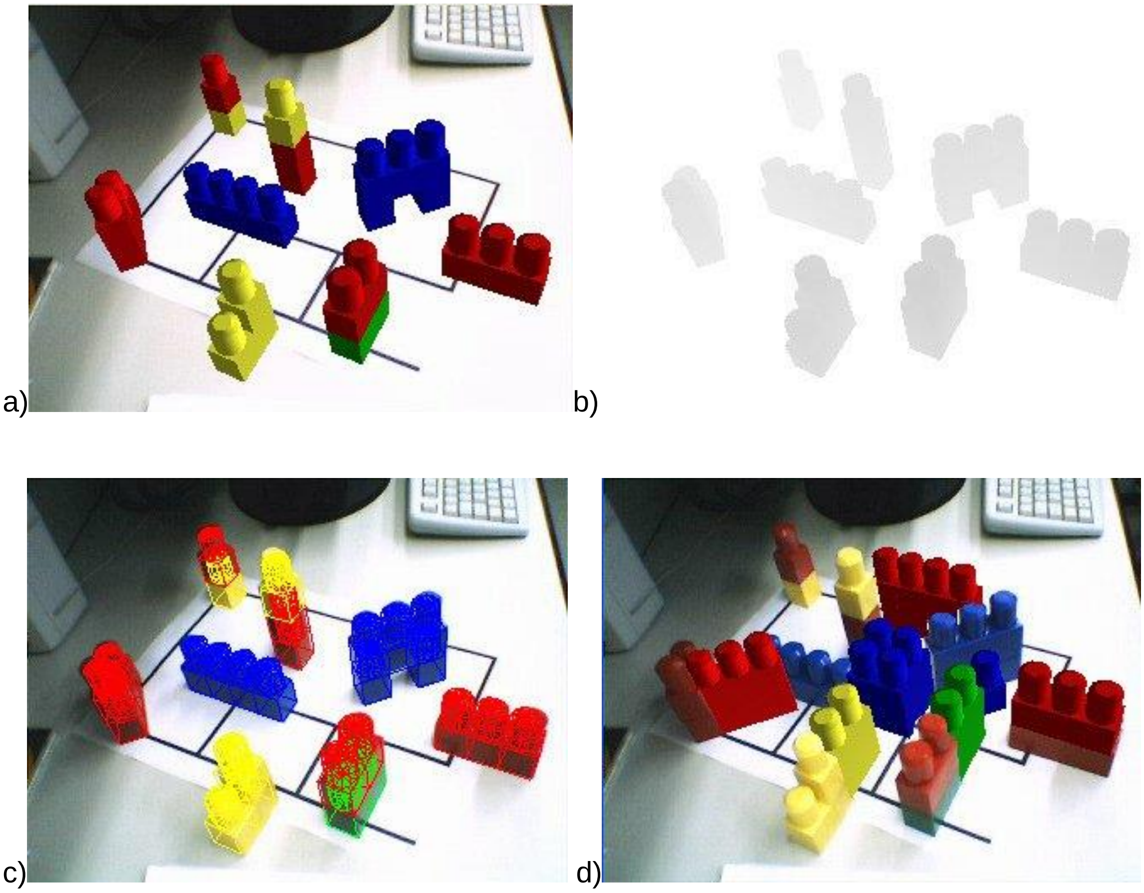


Figure 3-6 (a) "Ghost" virtual objects drawn in the render buffer and (b) in the depth buffer. (c) These objects are rendered in wireframe on top of the image of the real objects. (d) Image of the real objects composed with additional partially occluded virtual objects. (Sá *et al.*, 2007)

3.4.3 Camera Calibration

Whilst accurate tracking and effective occlusion handling are important factors towards compelling registration between the real and virtual worlds, inconsistency of viewing parameters between the virtual camera model and the real camera are also a major source of registration errors within an AR system (Azuma, 1997). For compelling registration, the view volume of the virtual camera (the portion of the viewing frustum between the near and far clipping planes) should be calibrated so that it is identical to that of the real camera. Furthermore, since the view volumes of both real and virtual cameras are a function of the focal length and detector plane dimensions (see Figure 3-7), it is possible to provide an identical view volume for the virtual camera by setting its focal length and detector plane size to be identical to that of the real camera being used by the system (Shin and Dunston, 2010).

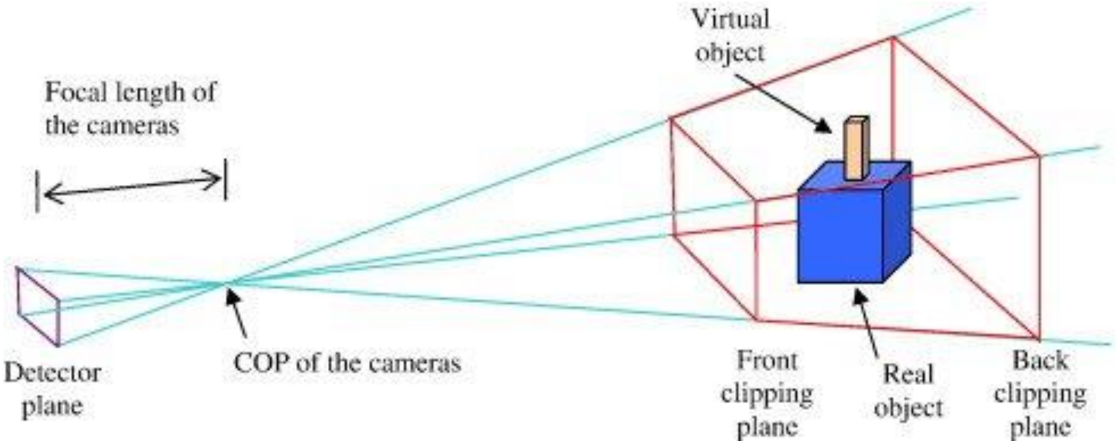


Figure 3-7 View volume of the virtual camera overlapping the view volume of the real video camera (Shin and Dunston, 2010)

Modern graphical Application Programming Interfaces (API), such as OpenGL, provide methods for modelling the view volume of a virtual camera by defining certain parameters. The simplest method of this creates a symmetrical viewing frustum that is defined in terms of the relative positions of the front (near) and back (far) clipping planes plus the angular difference between the top and bottom view planes, the Field Of View (FOV) and aspect ratio, the product of dividing the width (in pixels) of the image sensor by its height. However, a real camera will invariably not possess such symmetry due to offsets in the placement of the imaging sensor in relation to the Centre Of Projection (COP), therefore a further method can be used to create asymmetrical viewing frustums by defining the centre of the detector plane (the principal point) in relation to the sensor size, the COP and the focal length (Shin and Dunston, 2010).

Nevertheless, Sá *et al.* (2007) explain that without prior knowledge of the interior orientation and dimensions of the real camera's components, its intrinsic parameters, estimation methods for discovering them must be used. These include computer vision-based calibration routines in which calibrated image patterns, usually checkerboards, are analysed for salient points to track; this then enables the software to compare and track the points between several images and perform statistical data fitting routines on the results to provide estimations of the cameras intrinsic parameters (Shin and Dunston, 2010). Conversely a manual approach can be used, e.g. Santana-Fernández *et al*. (2010), in which spatially referenced 3D models of real world objects are superimposed upon the real scene viewed through the AR camera and the various parameters are adjusted within the application until the real and virtual are exactly aligned, thus iteratively arriving at the correct camera intrinsic parameters through experimental means. Additionally, this superimposition technique can also be employed to verify the results of camera calibration obtained by other means.

3.5 GPS

Previous sections have elucidated both the prevalence and suitability of GPS technology for ad-hoc position tracking within outdoor AR applications. Indeed, it has been suggested that as a system for general outdoor positioning and navigation activities GPS is seen as a 'first choice' technological solution (Rizos, 2005). However, while it provides an outdoor positioning solution that is freely available anywhere on the planet, there are certain constraints placed upon this capacity by hardware and environmental conditions. What follows is a brief description of the complete system setup, its technical limitations and techniques employed for their mitigation, though an exhaustive review of all the technical and mathematical attributes of this system is out of the scope of this work, therefore readers are directed to the excellent in-depth explanations in Farrell and Barth (1998) and Kavanagh (2003).

3.5.1 Global Positioning System Overview

GPS is structured as three interconnected segments: the constellation of 24 operational satellites constitute the ‘space segment’, the receiver equipment plus procedures for measuring and decoding the satellite transmissions are termed the ‘user segment’, while the third ‘control segment’ encompasses all operations and equipment for maintaining the accuracy of the system through a network of terrestrial monitoring stations (Farrell and Barth, 1998).

Technically, each satellite in the constellation orbits the earth every 11 hours 58 minutes at a height of around 20,000km in six different orbital planes, such that at least four satellites, but usually more, will always be visible to a GPS receiver anywhere on earth. Each satellite constantly transmits Pseudo Random Number (PRN) codes containing both ranging and navigation information to GPS receivers on the ground via a two-frequency radio link comprising the L1 and L2 carrier frequencies. Each transmission contains a unique Course Acquisition (C/A) code on the L1-band carrier frequency which is open and publically available, while the more accurate P code modulates both the L1 and L2 carrier phase and is reserved for military and governmental use under a service known as the Precise Position Service (PPS). The contents of the data streams transmitted by the satellites include parameters for satellite clock calibration, satellite position calculation, atmospheric correction, reference time and almanac and satellite health information and enable a receiver to make two distinct measurements known as pseudorange and carrier phase. These are then used by the receiver to provide positional measurements that range in accuracy from 10 – 15 metres for standard C/A code based point positioning, or down to sub-metre accuracy when working in relative positioning mode with two receivers using one of the differential techniques that are available (Kavanagh, 2003; Rizos, 2005).

3.5.2 Shortcomings and Issues

Despite its ubiquity and wide-spread use within many areas of work and leisure, there are many factors that can seriously impact on the accuracy and usability of GPS positioning technologies. Hammad *et al.* (2004) inform that, in addition to the number of satellites being tracked, the accuracy of GPS positioning is a direct function of the visible constellation geometry, as a well-spaced arrangement of satellites will enable the receiver to calculate position with a higher degree of accuracy. Atmospheric conditions leading to ionospheric and tropospheric distortions of the satellite transmissions lead to signal degradation. Similarly, orbital misalignment and satellite clock inaccuracies, together with multipath errors caused by signals reflecting from buildings, are also factors that contribute to incorrect or inaccurate readings at the GPS receiver. Furthermore, poor strength of the signal after travelling 20,000km results in it being easily blocked by tree cover or proximity to tall buildings and other structures within in an urban environment, the so-called urban canyon. However, Europe’s emerging Global Navigation Satellite System (GNSS), Galileo, which will consist of 30 satellites (27 operational + 3 active spares) operating with more complex and accurate signal and code structures, together with the recent improvements and upgrades to the Russian GLONASS GNSS system, promises to usher in a new era of accurate and reliable satellite based navigation, especially if the promise of interoperability between these various systems comes to fruition (Hammad *et al.,* 2004; Urlichich *et al.,* 2011; ESA, 2011).

3.5.3 Mitigating the Shortcomings

To obtain sub-metre or even centimetre accuracy with GPS requires either the use of a static base receiver and mobile rover unit working in differential mode and tracking the same group of satellites. The base unit can be a local GPS unit operated by the user, or a geographically local subscription service provided by a third party. Based on the ability to correct for errors caused by interference in the ionosphere and troposphere, orbital errors and clock misalignment between satellite and receiver, relative positioning approaches provide dramatic improvements in positioning accuracy. However as multipath signal errors and receiver noise will differ from receiver to receiver they cannot be corrected by these means. Typical accuracies afforded by this approach are three metres for standard Differential GPS (DGPS) and down to 5-10 centimetres for kinematic GPS (Peyret *et al.,* 2000; Roberts *et al.,* 2002a).

In operation, a base receiver is positioned at a known geodetic position on the ground from where it can calculate the offset between the known and received coordinate information, known as the range error or correction value. This measured error will be the same or equivalent to the error being experienced by the second rover receiver, and therefore can be used by the latter to correct its positional information by subtracting the range error value from its measured range values. This process can either be accomplished in real time by transmitting the correction value over a radio link, mobile internet connection or other suitable communication link, or later in post processing mode. Real-Time Kinematic GPS (RTK-GPS) utilizes a similar relative positioning approach to DGPS but, by using all available system measurements, including ambiguity in the carrier signal phasing, it is able to compute the vector between the 3D location of the antennas of the base and rover units at regular intervals (typically at least every second) enabling the level of positional accuracy to be increased some ten-fold (Peyret *et al.,* 2000; Hammad *et al.,* 2004). Of note however is that despite the reported accuracy levels that can be achieved by these methods, the actual accuracy displayed by the rover unit in either DGPS or RTK mode is directly impacted by the accuracy with which the base unit’s position is described during setup.

3.6 SUMMARY

This chapter discussed the technological implications and challenges regarding the enabling hardware and software components of an outdoor AR based planning system. It provided an exploratory review of current industry and research based practice surrounding the use of the individual technologies involved and of the implementation of these within AR systems.

Chapter 4

4 Research Methodology and Proposed Approach

4.1 INTRODUCTION

The previous chapters have presented a wide ranging review of construction planning techniques and tools. In particular, the salient issues with conventional construction planning practices were highlighted together with prominent mitigating approaches adopted in the research, particularly 4D CAD, advanced visualisation techniques and BIM. The enormity and complexity of the task facing a construction planner was acknowledged, even for experienced practitioners, who are still exposed to the potential pitfalls of information overload and mental 4D visualisation. Augmented Reality was presented as an advanced visualisation technique which shows potential for alleviating some of this mental load associated with construction planning. By providing contextual real time, real scale 3D visualisation of a construction product and process, AR would bring data to the user when and where it was needed. 4D CAD has made some inroads into the culture of the construction industry, however this is predominantly as a post planning review tool despite early research in the area highlighting its potential as a planning tool in its own right. Furthermore, Building Information Modelling was shown to be very much the future of data capture, storage and communication within the construction industry and yet to date it has not been leveraged for or during the planning phase.

This chapter will present a robust research methodology leading to the development of a conceptual framework and proposed approach for the implementation of a novel tool for interactively planning, visualising and capturing a construction plan. It is envisaged that the proposed interactive 4D approach will assist the construction planner by providing an iterative open ended planning environment in which they can freely interact with the geometry and data models of a proposed construction. Finally, a user evaluation protocol is described. This evaluation strategy will enable the level of compliance with the conceptual framework and proposed approach to be judged and the usefulness of the implemented tool to be ascertained.

Section 4.2 presents the generic research methodology employed in this study. Section 4.3 proposes a conceptual framework and proposed approach for the application of 4D CAD for interactive on-site construction planning. Based on the evidence highlighted in previous chapters, the salient attributes required for untethered outdoor BIM centric interactive 4D AR planning are discussed. Section 4.4 describes the user evaluation strategy adopted in this study to test an implemented prototype system (4DAR) against the attributes and requirements highlighted in the conceptual framework.

4.2 IMPLEMENTED RESEARCH METHODOLOGY

Fellows and Lui (2008) explain that it is only through the rigorous application of appropriate research methods and methodologies that the body of knowledge surrounding construction can be advanced and then established with confidence. However, many research efforts within the field of construction and the built environment have been criticised for their anecdotal approach to interpreting real world phenomena, reinforcing the need for a clear definition of the proposed research strategy from the outset (Amaratunga *et al.,* 2002). Furthermore, built environment research is not a clearly defined discipline. It is an applied field of study incorporating a wide array of subjects and approaches from mathematics through social sciences to the humanities. Therefore the methodological and epistemological assumptions of a study need to be made as clear as possible to avoid confusing both the issue and the intended audience (Knight and Turnbull, 2008).

This research study seeks to address the well-known problems associated with traditional construction planning practices through the application of advanced computer modelling and visualisation techniques. It moves towards the formulation of a novel method of schedule creation through the development of an innovative software tool. A generic four-part strategy was adopted to underpin the proposed research methodology used in this study: review, formulate, implement and evaluate (see Figure 4-1). The review entailed a detailed search and critique of prominent and emerging literature in the fields of construction planning, 4D CAD (3D + time), Building Information Modelling (BIM), Augmented Reality (AR) and associated supporting technologies. Following on from the literature review, a conceptual framework was established to support the development of the proposed approach adopted in this study. Using this approach, a novel prototype software tool was implemented, which was then evaluated by post graduate construction students and industry professionals to ascertain the usefulness of the approach, the usability of the tool and its level of adherence to the properties set out in the conceptual framework.

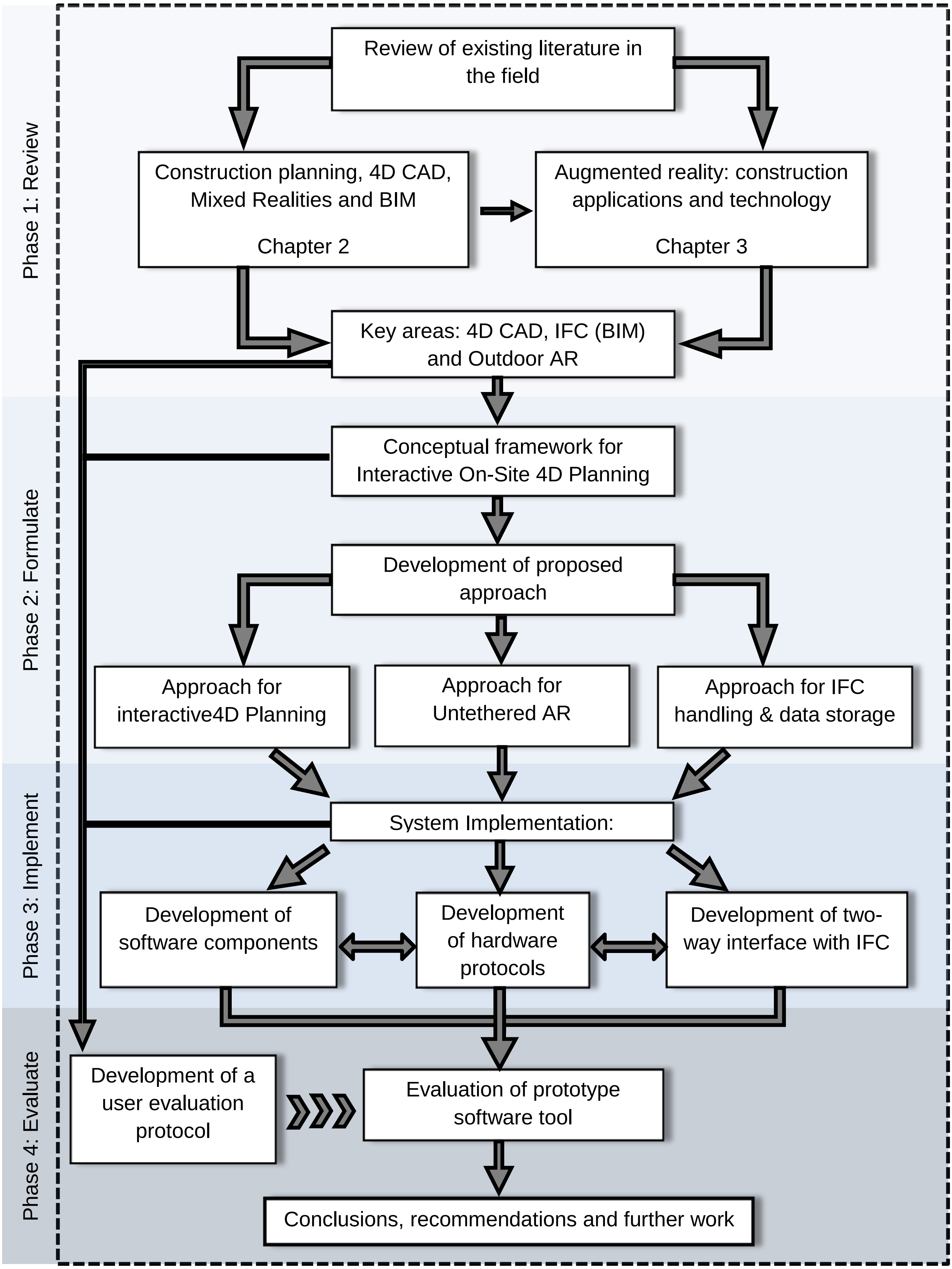


Figure 4-1 General Research Methodology

Knowing the current status of a body of knowledge is an essential first step in any research project (Iivari *et al.,* 2004 in Levy and Ellis, 2006). Levis and Ellis (2006) further explain that a literature search:

1) Facilitates an understanding of the existing body of knowledge, helping the researcher to understand ‘what is already known?’ and ‘what is needed to be known?’
2) Provides a solid theoretical base for the proposed study
3) Verifies the presence of the research problem
4) Validates that the proposed study contributes to the body of knowledge
5) Frames the research methodology, proposed approach, goals and research question

To establish the state-of-the-art in 4D CAD simulations, the shortcomings and problems with prevailing approaches and the extent of knowledge surrounding salient techniques for the mitigation of these problems, a literature review was carried out. Based on this review, key areas of interest were identified as having the potential to inform the development of a novel approach to 4D CAD for interactive construction planning:

- 4D CAD for plan creation
- Industry Foundation Classes (IFC) and the BIM data model file
- AR in unprepared outdoor environments

This critical review of prominent and emerging research provided a distillation of the major theories and literature in the field. In particular it highlighted advances made, and enabled the identification of the significant issues, shortcomings and potential solutions to enhance current 4D CAD techniques (Fellows and Liu, 2008; Naoum, 2007).

Following Seuring and Müller (2008), the wide ranging literature review informed and enabled the construction of a conceptual framework for on-site AR based 4D planning. From the conceptual framework, a proposed approach for real time construction planning using interactive 4D CAD, BIM and untethered outdoor AR was developed. Informed by the preceding research and proposed approach, a prototype software tool was implemented to enable on-site construction planning through interaction with the 3D model and BIM data, leading to the visualisation of a contextual 4D CAD simulation. Bernold and Lee (2010) explain how innovative technological methods or devices need to demonstrate their technical functionality through field testing, which also provides opportunities for feedback and improvement. Therefore, the implemented prototype was evaluated by industry professionals and post graduate construction students to enable assessment of the success with which the prototype realized the requirements set out in the proposed framework.

4.3 CONCEPTUAL FRAMEWORK AND PROPOSED APPROACH FOR INTERACTIVE ON-SITE 4D CONSTRUCTION PLANNING

The review undertaken in previous chapters revealed various limitations and potential opportunities in prevalent construction planning techniques and tools. Addressing the identified limitations with current approaches to 4D CAD led to the development of a novel framework for interactive schedule creation (Figure 4-2). The salient issues thus raised through the literature review can be divided into three discrete areas of interest:

- The limitations, potentials and requirements of 4D CAD
- The potentials and technical considerations of a wide-area outdoor AR system
- The constraints and potential for implementation of a BIM-centric workflow.

Informed by the preceding literature review and the salient points thus identified, a conceptual framework for interactive on-site 4D planning was developed. This conceptual framework seeks to highlight key issues identified in the literature review. This idealised framework intends to address problems identified with current construction planning practice (the planning domain) and the limitations and future potentials of 4D CAD approaches through the application of novel technological solutions (the technology domain), towards a robust and novel methodology of construction plan creation.

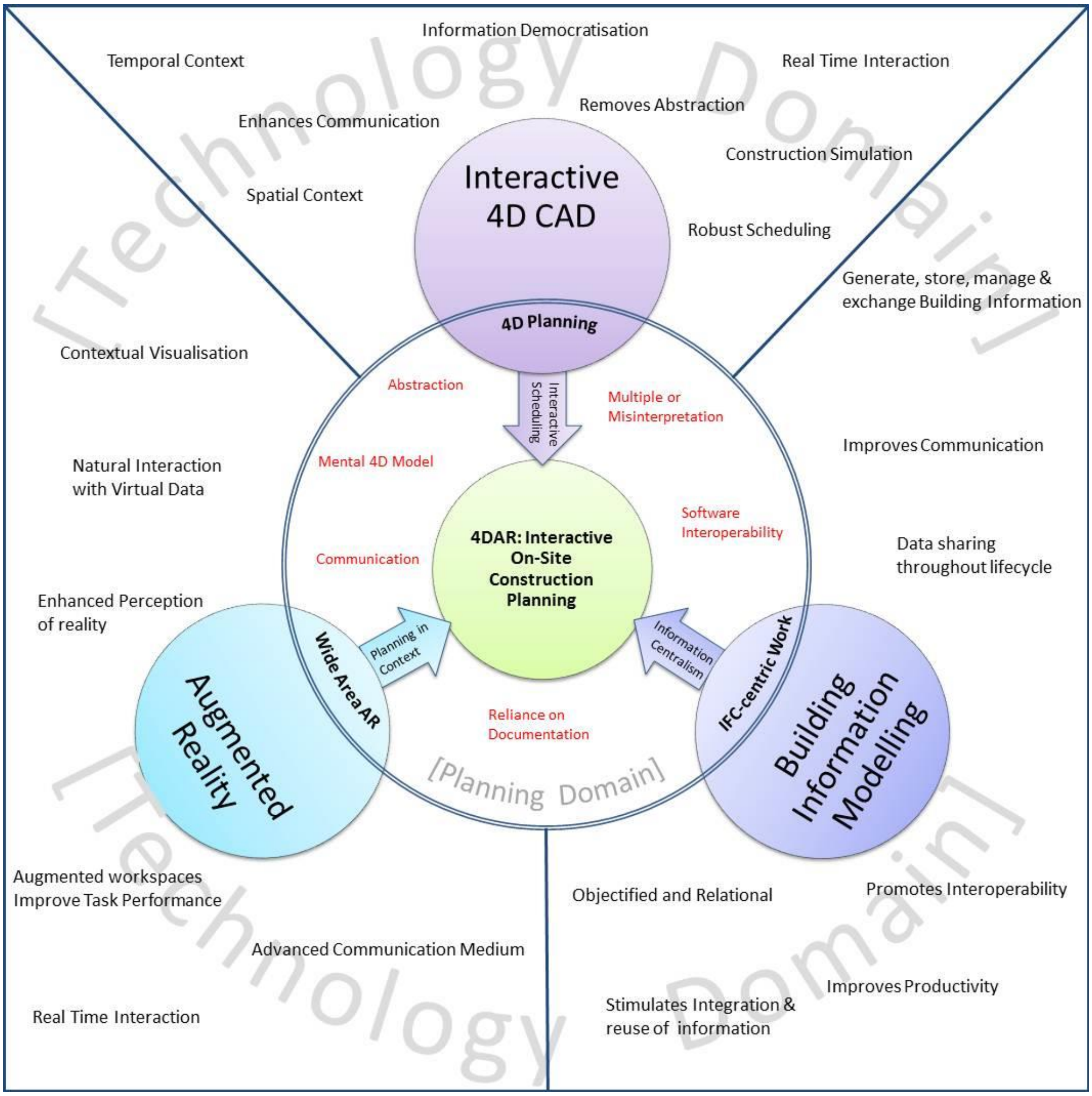


Figure 4-2 Conceptual Framework of 4DAR

It is envisaged that the application of this framework will enhance current planning practices by enabling contextual, iterative, visual planning through intuitive interaction with a building information model. Additionally, utilizing an open standard based workflow through the utilisation of IFC's will promote and enable more collaborative and coordinated planning practices, improved software interoperability and promote data centralisation in line with current UK government recommendations.

4.3.1 General requirements and proposed approach for an Interactive On-Site 4D Planning Tool

It has been determined from the literature review in Chapter 2, that a proposed 4D CAD tool for effective construction planning should demonstrate a number of generic requirements. These requirements relate to the ability to explicitly visualise Building Information Models, enable real time interaction towards the development of a construction plan, provide a planning approach within the context of the proposed construction site and utilise IFCs to centralise information and reduce documentation. Chapter 3 provided examples and highlighted the potential of advanced visualisation techniques such as AR to enhance the communication of complex information and data within a construction project. Current 4D CAD applications present a desktop-based approach for visual simulation of the construction process and product. However, the opportunity exists to extend its scope by taking 4D simulations out of the office using AR technology to enable 'contextual' 4D planning and visualisation.

4.3.1.1 Interactive 4DCAD

The use of 3D models during a building project provides unambiguous visualisation of the design intent that effectively democratises the design information and improves communication. Effective communication has been shown to be an essential component of a construction project. However, much research describes issues with communication during the planning and construction phases (Anumba and Evbuomwan, 1997; Anumba *et al.,* 2002; Isikdag and Underwood, 2010). Problems with current planning and communication techniques include the level of mental abstraction, the risk of multiple interpretations and the inability to combine spatial and temporal information (McKinney and Fischer, 1998; Koo and Fischer, 2000; Doulis *et al.,* 2007).

4D CAD techniques have been shown to mitigate many of the shortcomings inherent in construction planning approaches (Koo and Fischer, 2000; Staub-French and Khanzode, 2007; Kang *et al.,* 2007). Through the unequivocal visualisation of the evolving construction product 4D visualisations enable enhanced communication through information democratisation (Dawood and Sikka, 2008). Conventional approaches to 4D CAD create a link between the temporal data in schedule documentation and the spatial CAD data to form the visual 4D simulation. However, as the schedule has to be created *a priori*, this approach can be seen to be exposed to the pitfalls of conventional planning practices already outlined, whilst also relegating 4D CAD from a planning tool to a planning review tool only (Waly and Thabet, 2003). Using 4D CAD as a planning tool would leverage the planner's knowledge and creativity towards solving each unique scheduling problem, whilst negating the inherent pitfalls of prevailing planning approaches.

4.3.1.2 Outdoor AR

Planning requires individuals to understand and manipulate complex objects and relationships that do not yet physically exist. To enhance this process, Augmented Reality (AR) can be utilised to combine spatially referenced building models with the planner's view of the real world in real time to enable contextual 4D planning. It has been shown that this real time, real scale visualisation of a buildings form provides unequivocal visual representation. This in turn democratises the design information and reduces the risk of multiple or mistaken interpretations.

Robust registration between the real and virtual world is essential for maintaining the illusion of coexistence, yet tracking and registration are still the biggest challenges in implementing outdoor AR systems (Shin and Dunston, 2009). To afford such registration in an unprepared outdoor environment as a proposed construction site, sensors that do not rely on preinstalled infrastructure or equipment are required. Research has shown that the ubiquitous GPS system stands out as the best position tracking option for construction applications of AR (Behzadan *et al.,* 2008a). Issues with satellite occlusion and variable accuracy continue to affect GPS and while modern RTK-GPS systems are still vulnerable to these shortcomings, their successful implementation can improve accuracy on the ground by ten-fold. Orientation sensors that utilise naturally occurring phenomena, such as gravity and the earth’s magnetic field, also fit with an untethered approach to tracking the user’s movements around the augmented environment which is essential for implementing AR on a construction site.

4.3.1.3 BIM and the IFC

Conventional planning approaches employ a predominantly document-centric workflow. Research has highlighted how this approach can overburden a planning team with information and lead to multiple interpretations of the design and schedule (McKinney and Fischer, 1998). Furthermore, issues with software interoperability hinder coordination and communication efforts within the construction industry (Isikdag and Underwood, 2010). Building Information Modelling (BIM) is an approach to building design, construction and Facilities Management (FM) informatics that seeks to streamline the process of generating, storing and sharing building information data. This approach is further enabled through the provision of an open standard data model, the Industry Foundation Class (IFC). The IFC schema and the BIM standard in general have provision for the storage of data relating to scheduled construction tasks within a defined construction plan. Nevertheless, to date this capability of IFC to capture and utilise schedule information in the context of 4D construction simulations has not been explored.

Utilizing the rich objectified and relational information held within a BIM has the potential to add value to 4D CAD approaches by exposing information to the user regarding the physical and relational attributes of building entities. Utilising a 3D model as an interface to the voluminous amount information within an IFC file will provide an intuitive method for

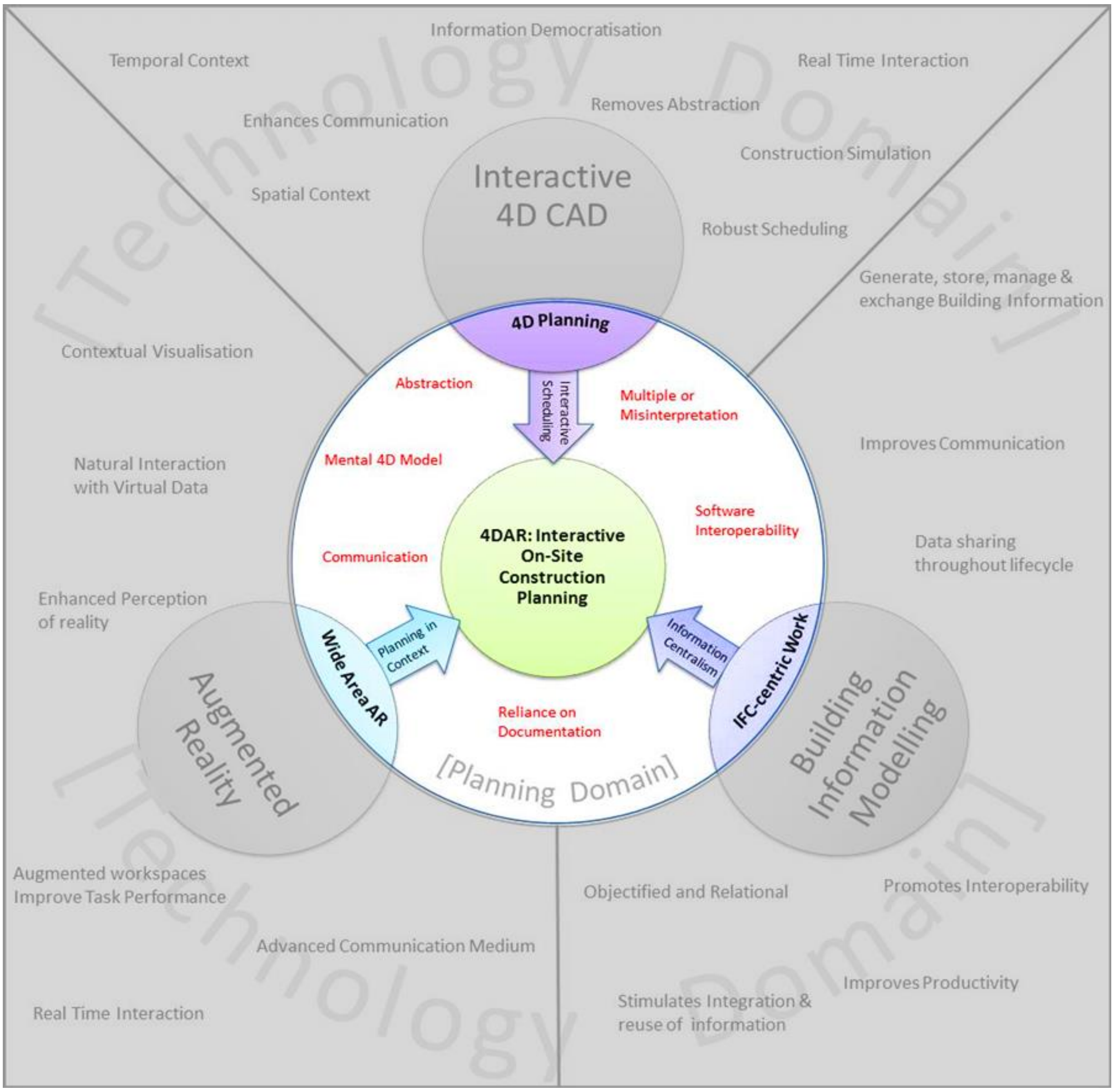


Figure 4-3 Technological solutions to problems within the Planning Domain

understanding and interacting with BIM data (Chen and Wang, 2009). Furthermore by providing mechanisms for capturing schedule and task information and storing it within the IFC file, a BIM-centric planning workflow would be enabled. This, in turn, will facilitate a more intuitive, streamlined and centralised approach to schedule creation, documentation and down-stream communication to be employed.

Based on the developed conceptual framework and proposed approach, a prototype 4D planning system was implemented that leverages the potentials identified within the three areas of interest (Figure 4-3). The implemented tool will enable a construction planner to interact with and visualise a 3D and 4D construction model in a real time AR environment. This intuitive interaction and visualisation approach will enable the formation of a robust construction schedule. Utilising untethered tracking technologies, i.e. GPS and electronic compass, the prototype system can be operated in unprepared outdoor environments, while the use of a HMD with a front facing camera provides the contextual visualisation of the 3D building model. The resulting sequence of tasks can be edited at any time prior to being committing to the IFC file, and is available for review as a ‘contextual’ 4D visualisation at any point in the planning process. Reviewing the sequence of tasks in this manner enables an iterative approach to planning whereby the suitability and robustness of a construction plan can be constantly checked by the planner before being committed to an IFC file for paperless storage and downstream communication.

4.4 DESIGN OF A USER EVALUATION PROTOCOL

Based upon the conceptual framework, a user evaluation strategy was developed to establish the validity of the implemented prototype tool. The user evaluation seeks to ascertain the effectiveness with which the implemented tool addresses the salient issues identified in the conceptual framework. Additionally, the evaluation procedure enabled construction professionals to appraise the “usefulness” of such a proposed system.

When implementing a computer based support system, it is important to both validate and evaluate such a system. Bornstein (1998) explains that validation tests a proposed system’s behaviour in relation to real world usage. He further elucidates that evaluation is the process of determining the value of a software system in relation to its usability and limitations (Borenstein, 1998). The 4DAR approach to construction planning is centred on the construction planner, providing tools and systems to support they’re decision making and providing the ability to visually represent the forecasting of real life situations. Therefore, employing a suitable user evaluation technique will enable the usefulness of the software tool and the idealised framework to be ascertained. Additionally, it will enable construction professionals to compare the proposed approach with conventional planning practices to assess the potential business benefits it may provide (Aouad *et al.,* 2000).

It has been reported that providing academics and industry practitioners access to prototype systems during their development stages is of much benefit (Heesom, 2004). However, performing a post implementation user evaluation can provide evidence of the overall worth of a software system (Boloix and Robillard, 1995). Indeed, Borenstein (1998) concurs that using independent assessors to evaluate a final prototype enables overall confidence in a system to be ascertained. He then goes on to identify the two main objectives for carrying out a user evaluation:

1) To test the suitability of the approach of a proposed system in relation to it’s possible users.
2) To assess the impact upon a proposed system of assumptions, simplifications and approaches employed during its development.

In addition, Boloix (1997) highlights how a user satisfaction evaluation can be employed to appraise the applicability of a proposed system. This evaluation should test the following three aspects from the users' perspective:

1) The level with which the software complies with its requirements
2) The usability and ease of use of the software tool
3) The contribution and potential benefits afforded by the tool

Using a non-probabilistic sampling method, suitable evaluators were selected from industry to evaluate the implemented prototype. Maxwell (1997) explains how, in quantitative research, non-probability sampling methods are viewed as "convenience sampling" but, within qualitative research studies, a third approach can be adopted: purposeful sampling (Patton, 1990 in Maxwell, 1997). This approach is primarily adopted in qualitative research studies when specific individuals or groups of people are selected based upon the precise area of interest the research question is addressing (Teddlie and Yu, 2007). In the case of this project it is envisaged that end users of the implemented prototype tool would be construction professionals, specifically planners and project managers. Within this context, the sample was deliberately predefined and subjectively chosen to be representative of the end user profile (Trochim, 2002).

Measurement can be defined as the process for assigning symbols, such as numbers to objects in a consistent manner to represent quantities or levels of specific attributes (Siegel, 1957; Viswanathan, 2005). There are four levels of measurement scales that can be employed within research studies: Nominal, Ordinal, Interval and Ratio. Each provides data in a form that is appropriate for specific statistical manipulation methods. However, it is the simple categorisation of objects in the Nominal scale and the ranking or ordering of objects using the Ordinal scale that are usually employed in nonparametric methods (Stevens, 1946;

Siegel, 1957; Conover, 1998). Ordinal questions are considered appropriate for use when the topic is well defined (Lumsden, 2007). Moreover, applying this method of measurement to the responses to questions enables comparison and equivalence to be measured. Therefore, this data will enable questions regarding proposed approach and system implementation to be compared and related to each other.

Employing a rating scale enables evaluators to express the direction and strength of their opinion on a topic (Garland, 1991). The use of a Likert-type scale within a user evaluation questionnaire enables the use of ordinal measurement techniques to capture the average opinion of the evaluators (Bailey, 1987 in Heesom, 2004). Generally, a 5 category balanced Likert scale is employed to measure a respondent's level of agreement or disagreement to a specific statement (Garland, 1991). However, Garland (1991) questions whether the inclusion of the mid-point introduces a social desirability bias arising from the respondents' desire to please or be helpful to an interviewer (Garland, 1991). Therefore, a balanced four point Likert-type scale was utilised in the design of the evaluation questions.

A web-based questionnaire was designed and implemented to capture the evaluators' responses in relation to this study using a Google Drive form document. Compared to paper-based questionnaires and other traditional survey methods, web-based questionnaires are inexpensive, fast, flexible and convenient in terms of design, distribution and responding (Lumsden, 2007). Moreover, there is growing evidence to show that there is no mode effect on the data collected by this method over traditional survey methods (Denscombe, 2006).

4.4.1 User Evaluation Sessions

The user evaluation sessions were comprised of three distinct units to enable a complete evaluation of the implemented prototype to take place. The first unit presented an overview of the research project, while a video presentation and tutorial were provided in the second unit to assist the evaluators to understand the context and the operational approach of the 4DAR prototype. The third and final unit provided a web-based questionnaire that enabled the evaluators to provide feedback on the proposed approach and implemented prototype.

The evaluators were first provided with a presentation that defined the background to the study and the research methodology employed. Additionally, a brief overview of the key areas of the proposed approach for interactive BIM-based construction scheduling in outdoor AR was given, together with an outline of the architecture of the implemented prototype.

The second unit in the user evaluation was based around a practical session where users could get “hands-on” experience of the implemented software tool. Studies have highlighted the problems of user discomfort and distraction when using an outdoor AR system due to ergonomic or hardware capability issues (Behzadan *et al.,* 2008b). Furthermore, the screen resolution offered by the low cost HMD employed proved to be a very limiting factor when using GUI components. Hardware design and wearable computing considerations were beyond the scope of this study, therefore evaluators were not asked to use the developmental system in an outdoor setting. Following a structured tutorial outlining the interactive, iterative construction planning process provided by the 4DAR prototype, a video of a 4D CAD simulation taken during a 4DAR developmental session was played. Each evaluator was then guided through a desktop-based planning session using the implemented tool.

The third and final unit in the user evaluation enabled the evaluators to comment and provide feedback on the potential usefulness of the implemented software prototype using a web based questionnaire form. This process sought to harvest the evaluators opinions as feedback regarding the functionality of the implemented prototype tool and its’ constituent functionality. Moreover, by utilising ranking techniques, the questionnaire sought to assess the extent to which each software module adhered to the attributes specified in the conceptual framework.

4.4.2 Design of the User Evaluation Questionnaire

Carrying out a post developmental user evaluation enabled two distinct types of information to be collected. Firstly, the opinions of the perceived end users of the implemented tool towards the viability of the approach to construction planning developed in this study (Sudham and Bradburn, 1982). Moreover, their opinions could be used to test the level of achievement attained by the implemented tool in term of the aims outlined in the conceptual framework.

The conceptual framework is comprised of 4 areas over two distinct 2 domains. Within the central planning domain are set out the key issues with current planning practice identified in the literature and the proposed interactive BIM centric planning tool which is presented in mitigation of these shortcomings. Around this core, is the technology domain within which are the three areas of interest: interactive 4D planning, wide-area outdoor AR and Building Information Modelling, which provide the technological terms of reference for the proposed 4DAR planning tool. The questionnaire was developed to investigate if the implemented tool addressed the issues within the planning domain through the application of the attributes identified within the technology domain.

The evaluation questionnaire was divided into four sections. The first section sought to acquire specific information about the evaluator to ascertain their level experience within the construction industry and in particular their familiarity with the technological approaches adopted within this project. The following three sections of the questionnaire related directly to the three technological approaches identified in the conceptual framework and adopted in the implemented tool. Each section sought to ascertain the evaluators' opinion towards the relevance of each specific technology in the context of construction planning. Questions were also asked regarding the level with which specific attributes of the technology, highlighted in the conceptual framework, were achieved within the implemented 4DAR prototype.

The following sections of this chapter provide an outline of the user evaluation questionnaire and highlight elements of the conceptual framework that were tested during the iterative BIM centric 4D planning process adopted in the implemented prototype.

4.4.2.1 Evaluator Background Information

The purpose of the first section of the questionnaire was to acquire information relating to each individual evaluator, including their job title and number of years' experience within the construction industry. This information could enable a correlation between type of practitioner and the perceived benefit of the prototype tool and proposed approach. In addition, this section also enquired as to whether the evaluator had experience with 3D CAD tools. The implemented tool employs a novel approach to construction planning operations that is designed to be used without prior knowledge of existing design, visualisation or planning applications. Nevertheless, if the evaluator has prior experience with 3D CAD tools, they may find the implemented system more intuitive.

Currently, commercial 4D CAD tools provide only post-planning review functionality, requiring a construction sequence to be scheduled in the traditional manner before being linked to a 3D model for sequence visualisation. The evaluator is next asked if they have experience of existing 4D CAD tools, as this may affect their opinion of the proposed 4D planning approach. Central to the 4DAR approach to construction planning are the areas of augmented reality (AR) and Building Information Modelling (BIM). Applying a BIM centric, IFC based approach to construction planning would both centralise and reduce the amount of documentation associated with the planning process. The final three questions in this section seek to ascertain the level of the evaluators' familiarity with these core technologies, including the BIM data model file the IFC.

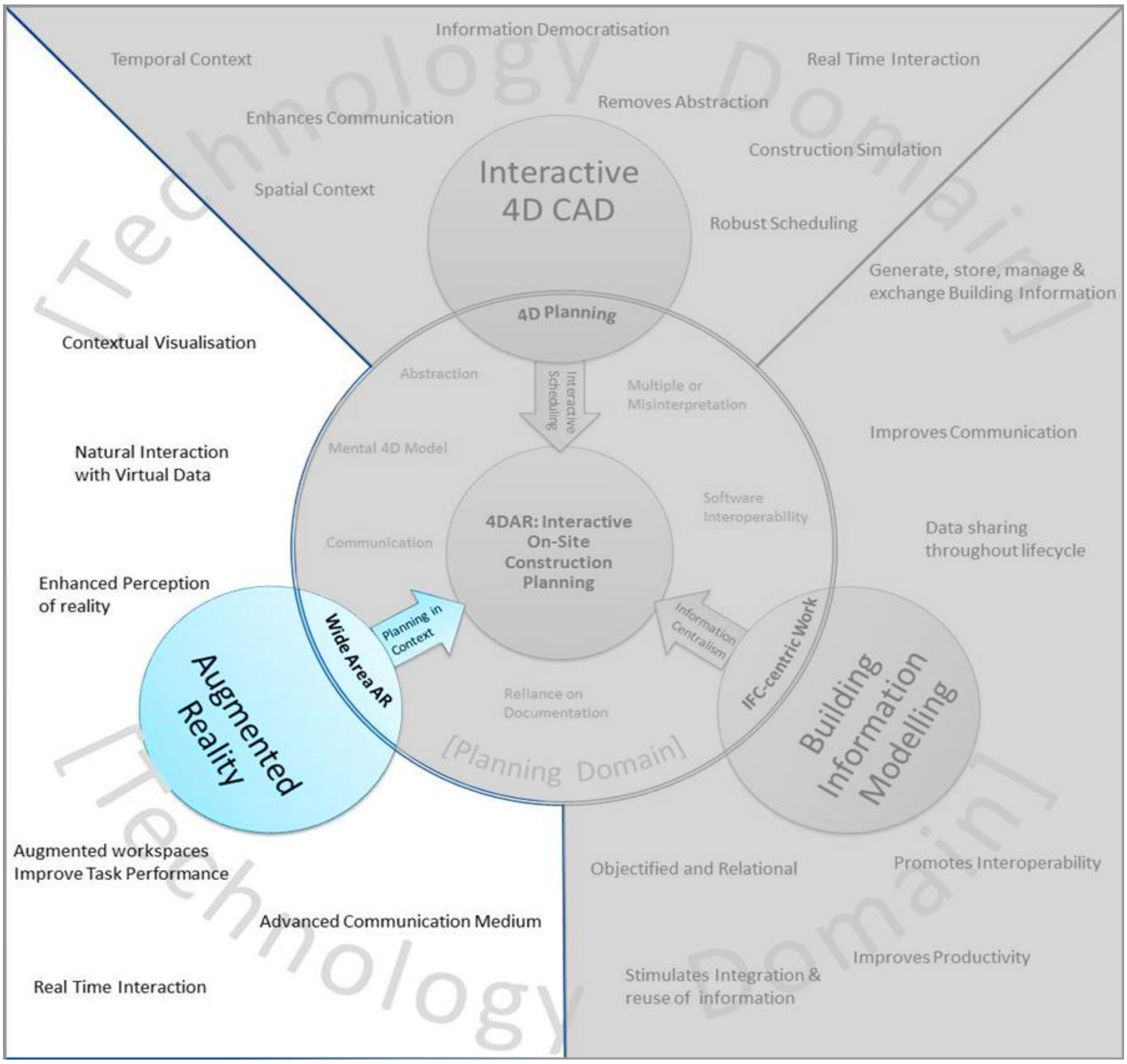


Figure 4-4 Technological attributes of AR

4.4.2.2 Augmented Reality in Construction

This section of the questionnaire sought to obtain the evaluators opinion regarding outdoor AR as an interaction and visualisation method for 4D construction planning and within the wider context construction industry as a whole.

The evaluation questionnaire relating to the application of AR technology within the construction planning process aimed to test the validity of the proposed approach derived from the attributes highlighted in the conceptual framework (see Figure 4-4). It sought to evaluate the value of this technology's ability to visualise a 3D building model in a real world location and at full scale during construction planning. In addition the evaluator's opinion was tested on the potential of this contextual visualisation technique to add value to and improve communication and understanding of a planned construction sequence.

Finally the evaluator is provided with an opportunity to comment on the future potential, as they see it, for untethered outdoor AR technology within the wider context of the construction industry as a whole. This three point ordinal question precedes an open question containing a list of four potential fields. Three fields are populated with potential areas in which AR could be leveraged. The fourth is an empty field in which the evaluator can suggest an area or task they feel would benefit from the application of AR.

4.4.2.3 Interactive 4D CAD

The evaluation of the process of interactive 4D planning aimed to test the effectiveness of the technological attributes identified in the conceptual framework (see Figure 4-5). Furthermore, it evaluated the specific attributes associated with 4D CAD based planning through the interaction with a 3D building model within the implemented tool.

Initial questions relating to the usability of this component were presented to the evaluators. Realised predominantly by the View and Model modules, the GUI components were evaluated for suitability and ease of use. The traditional 4D CAD approach of manually grouping and associating objects with corresponding scheduled tasks is a tedious and time consuming task that is not required in this proposed approach. The evaluators were asked to evaluate the method of assigning date ranges to selected model components as a way of creating scheduled construction tasks.

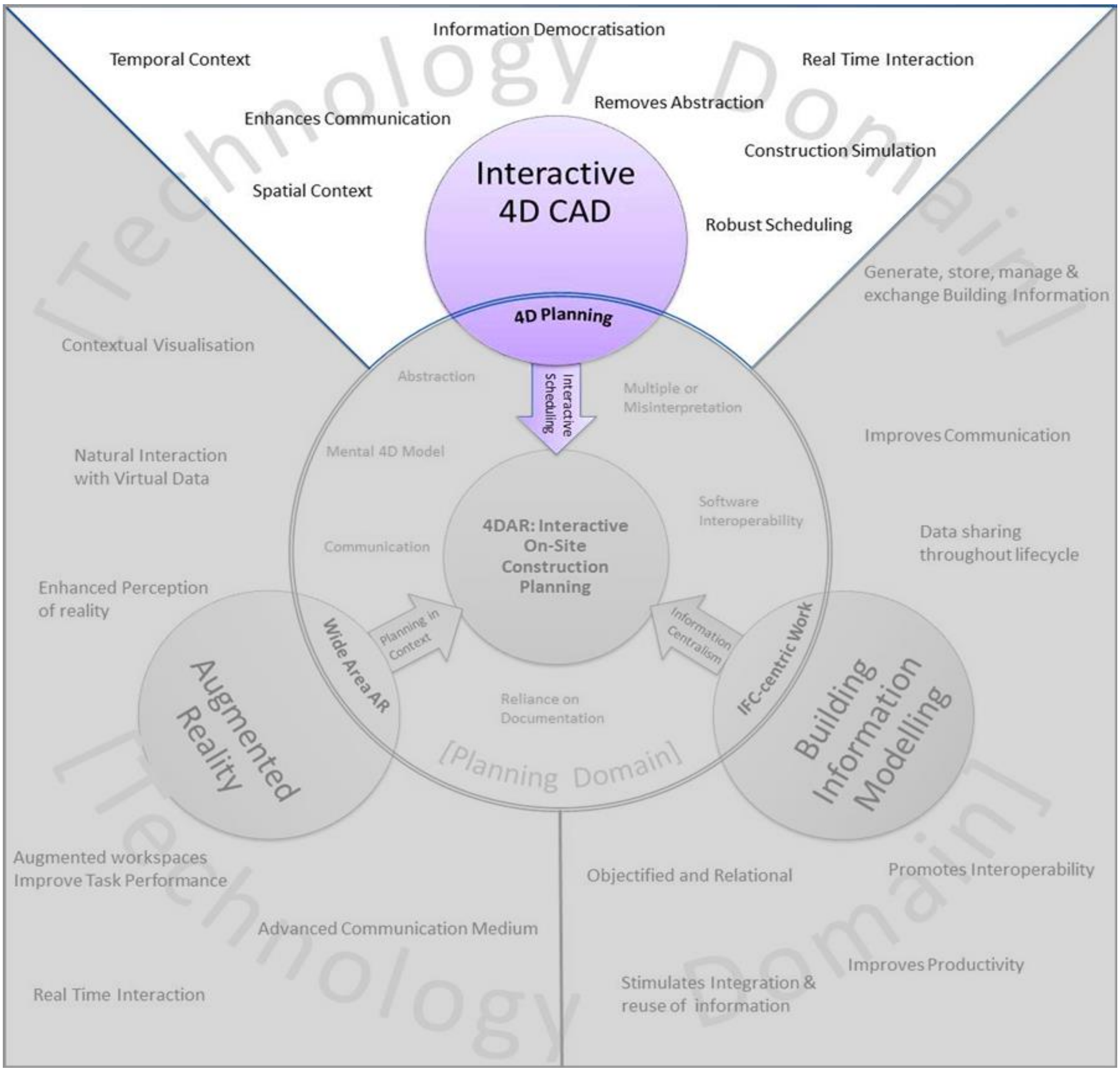


Figure 4-5 Technological attributes of Interactive 4D CAD

4D CAD simulations provide unequivocal visualisation of a construction sequence. This functionality is provided within commercially available 4D CAD solutions by linking schedule information with 3D CAD objects providing post planning review. To enable robust iterative 4D planning within the implemented prototype, the 4D visualisation can be viewed throughout the planning process. The evaluators were asked to comment on the usefulness of this approach. The potential of the iterative, interactive 4D CAD approach to construction planning leveraged in the implemented prototype was tested in comparison to traditional planning approaches. The evaluators were then provided with an open ended opportunity to provide further comment and opinion on this final point.

4.4.2.4 BIM in Construction Scheduling

A core aspect of the implemented prototype is the use of Industry Foundation Class (IFC) files within the planning process. In the context of attributes identified within the idealised framework, the viability of IFC enabled planning approach was evaluated. Additionally, the potential interoperability, communication and productivity benefits afforded by BIM / IFC adoption within construction planning and the construction industry as a whole is examined (see Figure 4-6).

Attributes relating to the potential benefits afforded construction planning by the objectified and relational data within IFC files were explored. By leveraging intelligent relational BIM data intelligent sorting, grouping and selecting of 3D building model components within the implemented prototype was supported. Furthermore, this approach enabled a mapping mechanism to be deployed between the geometrical and data models of the building employed in the implemented prototype. This approach enabled the user to interact with a sub section of BIM data within a lightweight graphical environment whilst providing the underlying ability to read and write construction planning information to and from the IFC file.

This ability to enable real time interaction through asynchronous mapping of IFC data to 3D geometry was examined to establish its benefit within a 4D planning environment. Finally, the usefulness of an overall BIM centric approach for construction documentation was examined, in which the evaluators were provided with an open opportunity to further explain their position on this central feature of the implemented prototype.

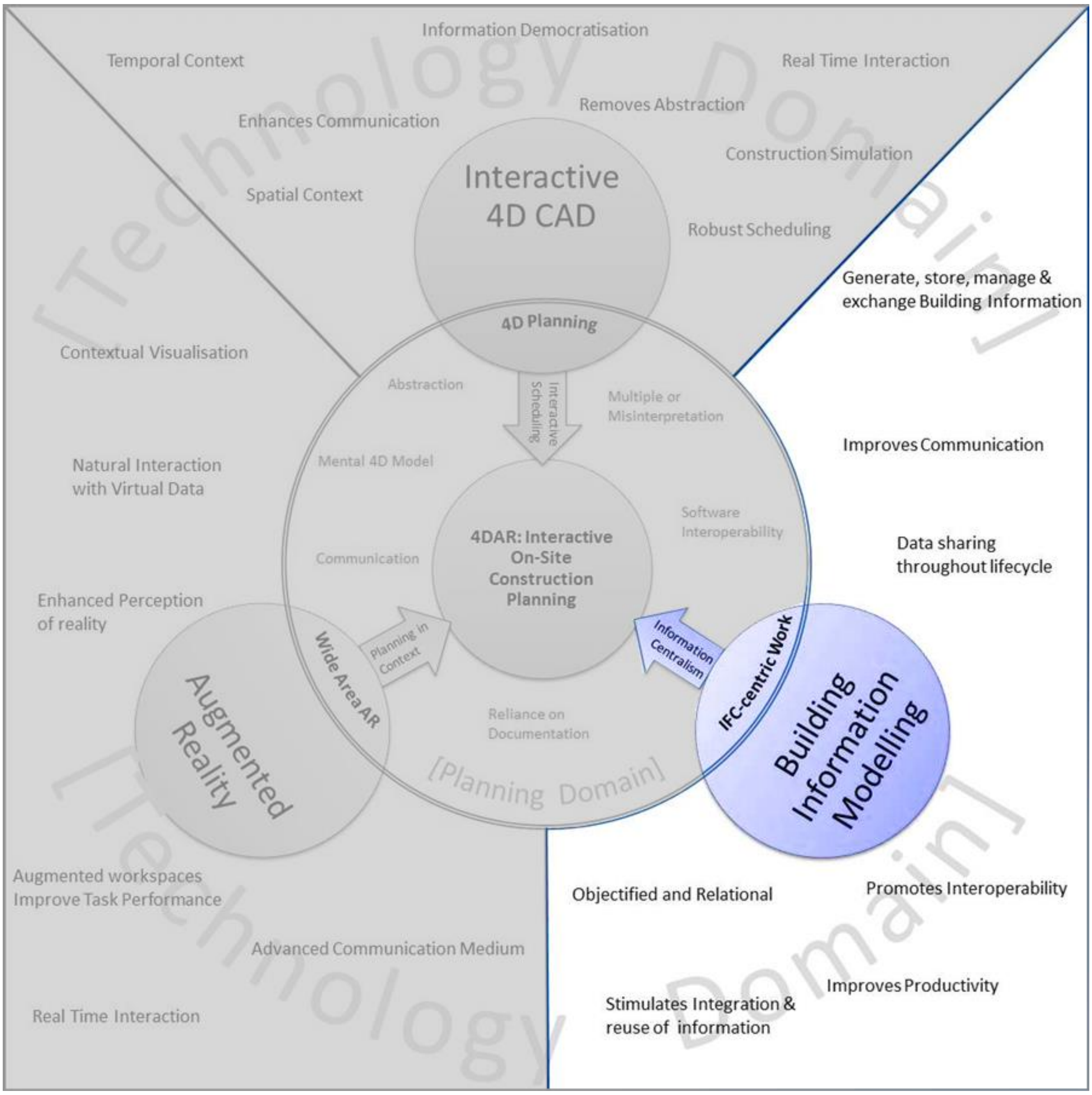


Figure 4-6 Technological attributes of BIM

4.5 SUMMARY

This chapter presented and discussed the four part generic methodology employed in this study. Also presented was the idealised conceptual framework for the development of an on-site interactive 4D planning tool. This provides all required attributes, including supporting technologies and the proposed approach required to address the identified shortcomings with current planning practices and 4D CAD tools. Based upon the idealised framework, the generic requirements and proposed approach were discussed for the development of a system for graphical contextual two-way interaction with a building's data model.

To enable the evaluation of the framework, proposed approach and the prototype system subsequently implemented, a user evaluation strategy was discussed. The strategy employed a practical user evaluation session followed by a user evaluation questionnaire. This sought to gain the opinions of construction professionals and post graduate students towards the implemented prototype system, whilst also assessing the success with which the prototype implemented the attributes from the conceptual framework.

Based upon the literature reviewed in the previous chapters and the problems associated with current planning methodologies and commercial 4D CAD approaches, this study concentrates on the following areas:

- Dynamic iterative construction planning using a real time 3D interface.
- Interactive 4D CAD for simultaneous plan creation and sequence visualisation in untethered outdoor AR.
- Two-way interaction with BIM data though the asynchronous mapping of 3D model elements with corresponding IFC objects.

A central element of this study was the development of a novel methodology for construction planning. This proposed technique uses a 3D building model as a graphical interface to the underlying BIM data. This approach also employs outdoor AR visualisation technology to enable the planner to create scheduled tasks through an intuitive interaction paradigm within the context of a proposed construction site. Leveraging the intelligent relational data within the BIM enabled intuitive identification and group selection mechanisms to be developed within the 3D environment. Inherent but underused relationships and data objects within the IFC schema were exploited to enable the capture of user defined schedule information. Furthermore, schedule data within an IFC file can be loaded into the system where it can also be visualised, edited and (re)saved.

The potential capabilities and shortcomings with current 4D CAD approaches have been identified by this study and addressed through the development of an interactive 4D planning approach. This seeks to create the construction schedule in real time through an interactive iterative approach to 4D planning and visualisation. By negating the need to create a schedule *a priori*, this approach also avoids many of the potential pitfalls associated with traditional construction scheduling, such as the divergence of the temporal and spatial information and potential mental overload due to the volume of documentation employed.

This issue with voluminous and fragmented documentation within traditional construction planning is addressed by this research through the utilisation of BIM data in the form of IFC files. This open standards based data model file is used as container for capturing the construction schedule information for storage, visualisation and downstream communication. Used thus, this approach holds the promise of greatly reducing the amount and diversity of schedule documentation, capturing all of a building projects data in a single repository, whilst being in line with current UK government initiatives within the construction industry as a whole.

Based on the approach presented in this chapter, the following chapter describes the development approach and implementation of a prototype system for on-site computer based 4D planning called 4DAR.

Chapter 5

5 System Implementation – Development of the Interactive On-Site 4D Planning Tool (4DAR)

5.1 INTRODUCTION

The previous chapter set out the four part research methodology employed in this study, discussed issues relevant to research in construction and the built environment and presented a conceptual framework and proposed approach for interactive on-site 4D construction planning. This chapter reveals the architecture of the prototype 4DAR planning system that was implemented based upon the conceptual framework, including software design influences, developmental and operational concepts, interfaces with and choices of hardware and the module-level processes that constitute the 4DAR prototype.

Section 5.2 provides a high level overview of the system architecture including the application of software design patterns, the integration of the individual software and hardware modules and the data input and output considerations. Section 5.3 presents the developmental approach adopted during the prototype development, including hardware set up, design considerations and operational concepts applied during the development process. Section 5.4 describes the Controller Module of the implemented system; its responsibilities within the applied framework and its functionality within the prototype system. Section 5.5 outlines the functionality and data flow considerations of the implemented View Module that provides an interactive 3D model as an interface to the BIM data. Section 5.6 considers the implemented Model Module, its functionality, concepts and enabling software tools and algorithms that allow a planner to work with a 3D building model as an interface to the underlying BIM data in the form of an IFC file. It highlights the algorithms developed to provide the data I/O functionality that supported the reading and writing of IFC data and the mapping of internal 4DAR data to IFC objects and relationships. Section 5.7 highlights the related Compass and GPS Modules that communicate and retrieve data from the tracking hardware utilised in the development of the prototype system.

5.2 4DAR: SYSTEM ARCHITECTURE

Selecting an appropriate system architecture is a serious consideration in the software development process (Madeyski. and Stochmiałek, 2005). Software design patterns describe reusable solutions to common software design problems (Isikdag and Underwood, 2010). The 4DAR prototype tool is based around the development of a layered software framework. Following Isikdag and Underwood (2010), the individual software components are integrated into the 4DAR tool using an approach based upon the Model-View-Controller (MVC) software design pattern, in which the simulation model, the visual display and user interactions are decoupled and handled by three separate modules or layers, the Model, the View and the Controller (Burbeck, 1987) (see Figure 5-1).

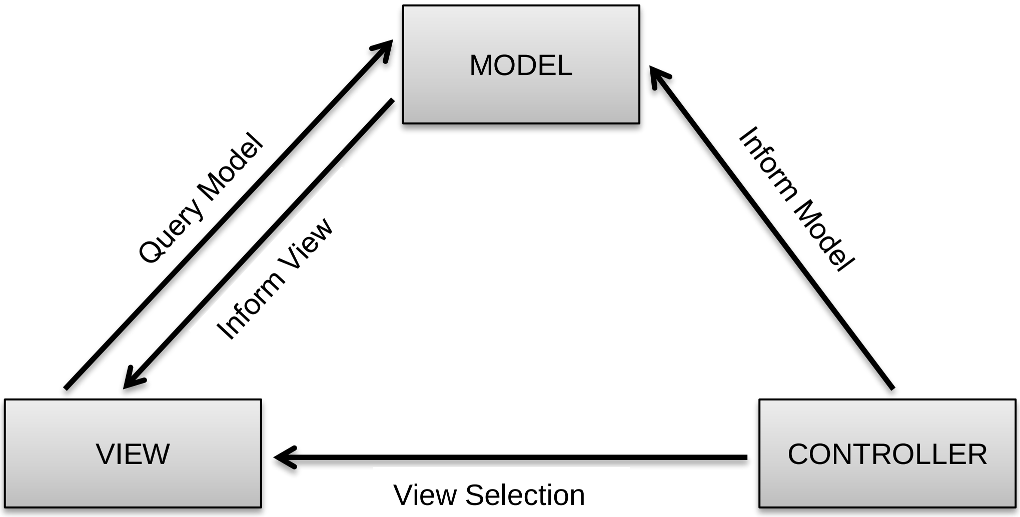


Figure 5-1 The M-V-C Software Design Pattern

Originating from the SmallTalk-80 interface programming language, the MVC metaphor quickly became the core idea behind user interface implementation in most object-oriented programming languages and is considered an archetypal method for module decoupling and integration (Veit and Herrmann, 2003; Madeyski and Stochmiałek; 2005). By separating the user interface considerations from the underlying domain model, the MVC paradigm breaks up the programming task into convenient chunks and makes it easier to change one module without affecting the others (WorldViz, 2011). Krasner and Pope (1988) further explain how utilizing this programming metaphor not only assists with the conceptual design of interactive applications but enables the reuse of software components.

The Model in MVC is considered to be the component that does the work of simulating the application domain, prescribing its logic and keeping track of its state during operation. The View manages all graphical representations of the model, while the Controller handles all user interaction and provides communication between the Model and View and the user and the Model. The View is required to be quite tightly coupled with the Model component to enable the correct visualisation of the data held in it. However, the Model is developed independently of specific display and interaction methodologies. This arrangement means that each View-Controller pair can be linked with just one Model, whereas each Model can be associated with many View-Controller pairs (Krasner and Pope, 1988; Madeyski and Stochmiałek, 2005; Isikdag and Underwood, 2010).

Based upon the MVC design pattern, a 4DAR module was developed to manage the underlying domain model and application logic: the Model (Figure 5-2). This module accepts as inputs an OpenSceneGraph (OSG) 3D model of the proposed construction project and the corresponding IFC file from which the 3D model file was generated. To facilitate an interactive visual scheduling paradigm, the geometric building elements within the 3D model are associated with their equivalent elements within the IFC file and the information subsequently retrieved is held as attributes of the corresponding 3D elements. Making BIM data directly accessible within the virtual environment enables intelligent grouping and selection methods to be employed. Additionally, it enables a flow of information from the planner back to the IFC file. The resulting information-rich visual model facilitates the scheduling of construction tasks through two other modules, the View and the Controller.

User created schedule information is held within a nested data structure by the Model to facilitate 4D functionality and schedule information capture back to the IFC file. Schedule information, already present within the IFC file, can also be loaded by the system and manipulated in the same manner as user created schedule information.

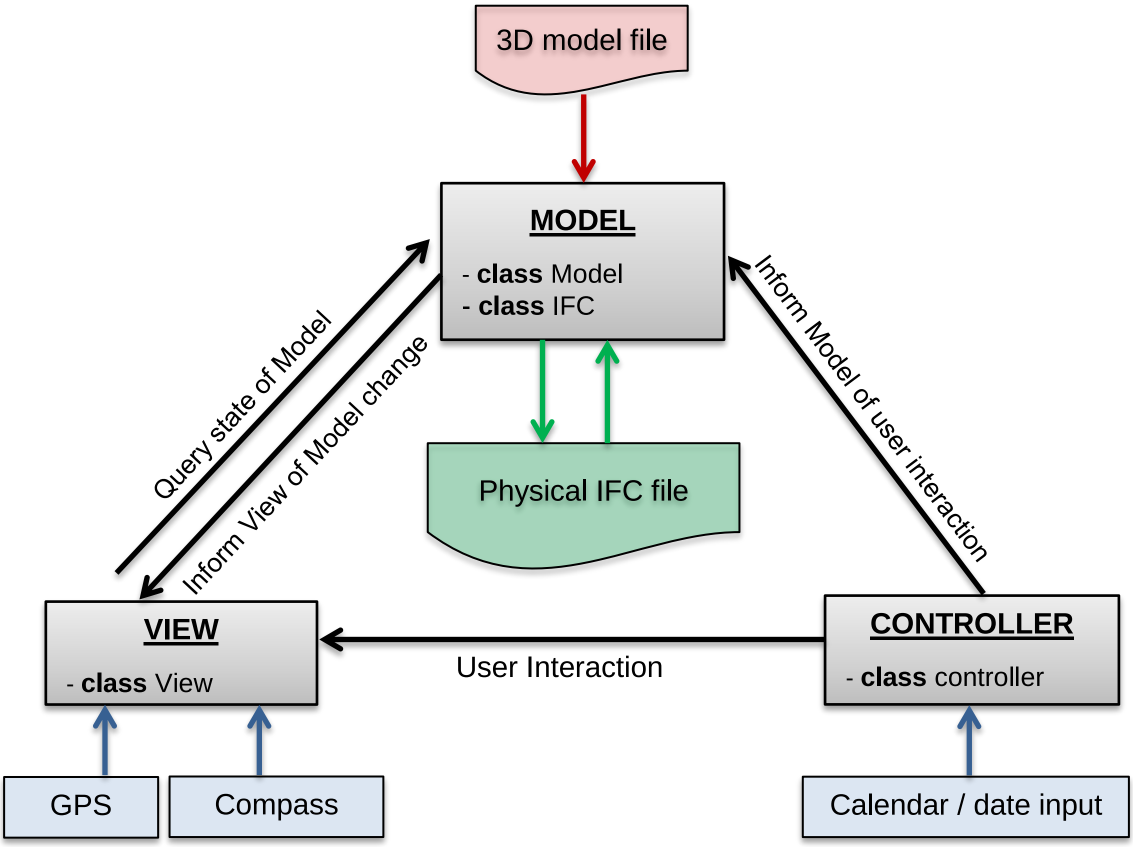


Figure 5-2 4DAR System Architecture

As previously described, the user interaction layer in MVC is composed of two modules, the View and the Controller (Figure 5-2). Within 4DAR, these two modules enable the formulation of a construction schedule by providing a visual representation of and interaction with the underlying BIM data. The user interacts directly with the 3D model components to assign construction dates either individually or as part of a group. The Controller captures all user-system interactions and the resultant schedule information is stored by the Model and utilized by the View to provide 4D visualisation of the proposed construction schedule.

Further modules are utilized by the View module to enable connection to the tracking devices utilized by 4DAR. By utilizing the data from an electronic compass and an RTK-GPS unit to position and orient the virtual camera within 4DAR, the View combines (registers) a geo-referenced 3D model loaded into the system with the input from the head-mounted camera worn by the user to provide an outdoor augmented planning environment visualised through a head mounted display unit.

5.3 DEVELOPMENTAL APPROACH

The 4DAR prototype system was implemented on a Microsoft Windows based PC platform using the Vizard VR Toolkit from WorldViz. The Vizard VR Toolkit is an authoring tool that provides an Integrated Development Environment (IDE) that gives access to a real time rendering engine through an extensive Python module library. Using an interpreted Python programming environment to abstract the functionality of Vizard's internal render engine enables shorter developmental cycles to be employed than lower level compiled languages allow (Schaul *et al.,* 2010). Furthermore, it gives access to the vast array of specialist module libraries that can be freely downloaded and easily employed to augment the base features of Python. Two such 3rd party modules are employed within 4DAR; pySerial which provides native python serial port access and pywin32 that gives access to various Microsoft API's, including the COM or automation interface. The pywin32 module is used to enable the manipulation of the ActiveX component IFCsvr.R300, an IFC data handling development tool developed by SECOM Co. Ltd that utilizes the STEP-Tools ST-Developer SDK (SECOM Co., Ltd 2005). The software also requires the JavaScript calendar widget, JSCal2 (Dynarch.com, 2009). This DHTML object is embedded within a HTML form to enable date ranges to be submitted back to the Vizard application and is used to describe the start and end dates for a schedule task.

5.3.1 Hardware Setup

The software modules that provide the functionality for the 4DAR prototype are based around open standards both in terms of file formats utilised and supported hardware interfaces. Therefore, whilst specific tracking and visualisation equipment was chosen to support the development process, the functionality of the 4DAR prototype is not dependent upon any such specific hardware but rather the protocols that the hardware supports.

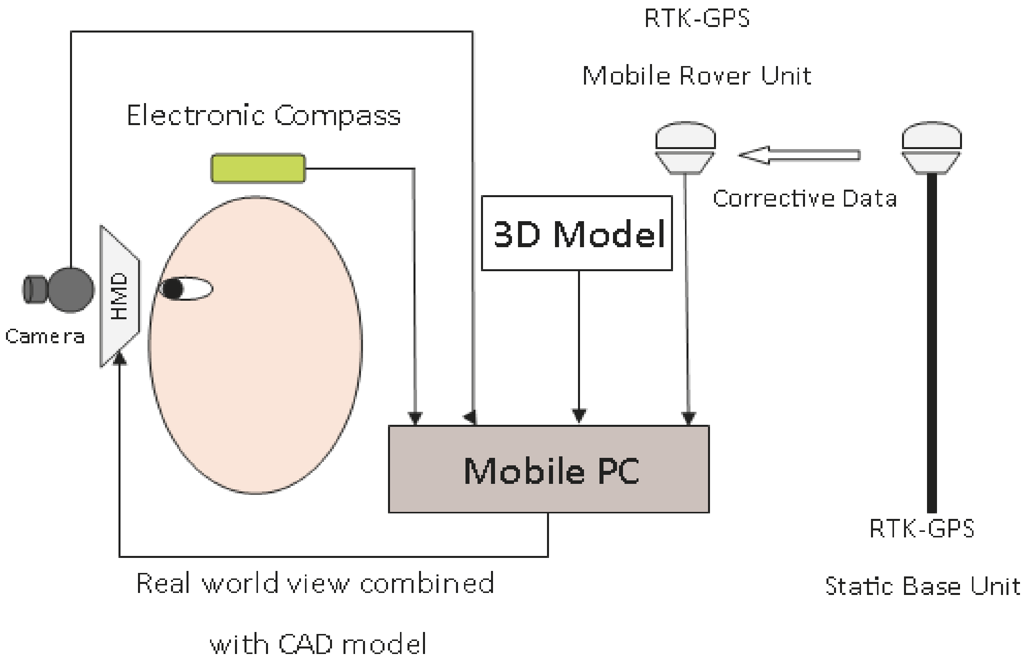


Figure 5-3 4DAR Hardware configuration

A Head Mounted Display (HMD), with a front facing camera unit, is employed to provide hands free visualisation of the interactive augmented environment. To create the AR environment, a geo-located 3D building model is loaded into the scene via a mobile computer which is connected to GPS and compass modules to provide the 4DAR prototype with location and orientation data (Figure 5-3). 4DAR uses this positional data to register the 3D model in the correct location in relation to the view of the real outdoor environment that is streamed from the front facing video camera. Furthermore, the viewing frustum of the virtual scene camera was calibrated, based upon the manufacturers data (Santana-Fernández *et* *al.,* 2010) so that it coincided with the frustum of the physical camera to provide compelling registration between the real and virtual scene content.

The HMD utilised during the development phase of this project was the consumer level iWear VR920 headset with the iWear CamAR camera unit, both made by Vuzix (Vuzix Corporation, 2010a; Vuzix Corporation, 2010b). The CamAR unit is capable of streaming a video frame of 800 x 600 pixels at 30fps (frames per second) and was manufactured to clip securely to the front of the chosen HMD. Its standard USB connection meant that it was detected as a conventional video camera unit and therefore could be substituted for any standard video device. The VR920 HMD provides an LCD screen for each eye which gives the illusion of a 62 inch (1.5748 metres) screen viewed at a 9 feet (2.7432 metres) distance. The small field-of-view (32 degrees) and the poor resolution of this unit (640 x 480 pixels) impacted somewhat negatively upon usability. Nevertheless, in use it proved satisfactory for viewing a 3D model in-situ against the video background, while menu items and on-screen GUI items were less well provided for. This HMD unit also incorporates a basic 3DOF orientation tracker; however it exhibits quite marked noise even after calibration and yaw drift of up to 25 degrees (to the right) when pitching up or down. Consulting the forums for the product, it was discovered that the yaw is measured by a compass (magnetometer) only and the pitch and roll are measured by accelerometers. The inability to offset the shortcomings of one sensor with the strengths of a different type around the same axis, so called sensor fusion, means it is not possible to negate these shortcomings programmatically (Azuma *et al.,* 1999b; Schall *et al.,* 2009b).

The GPS and compass units used for position and orientation tracking within 4DAR employ a serial port connection and standard NMEA (National Maritime Electronics Association) data handling protocol to enable their data to be read in real time. Therefore, although developed for specific equipment, the interface created is general enough to allow connection to any equivalent equipment that uses this standard communication protocol. This approach enabled various GPS equipment set-ups to be used during the development of the 4DAR prototype, while RTK-GPS provided the best positional accuracy and granularity of data output (Roberts *et al.,* 2002b; Schall *et al.,* 2009b), it was possible to utilise standard consumer GPS units that supported NMEA streaming either via Bluetooth or wired serial port connection.

The compass unit used was the OS5000 digital compass unit by (OceanServer Technology Inc., 2011) and was originally developed to provide heading information for autonomous underwater vehicles. This 25mm x 25mm unit comprises of 3-axis magnetic sensors fused with 3-axis accelerometers to provide a 3DOF tilt compensated (electronically gimballed) compass that has a cited accuracy of up to 1° < ± 30° tilt, negating the yaw drift experienced with the native tracking of the Vuzix HMD. Additionally, it provides calibration routines although in practice it proved difficult to accomplish perfect calibration due to the required constraints, i.e. rotating around each axis within 1° of level for that axis using completely non-ferrous equipment (OceanServer Technology Inc., 2010) . A moving average filter is also incorporated to combat the effects of sensor noise. This approach does introduce latency into the system. For instance, with the compass update rate of 40Hz and the filter set to average over 8 samples, a small but perceptible delay of 200 milliseconds was introduced. Reducing the sample range reduces the latency with the trade-off of introducing more noise, which in use was found to be less desirable than a slight latency in head tracking. This sensor was mounted on a standard safety helmet and despite the difficulty with calibration proved to be more usable in operation than the tracking provided by the HMD. However, its stability and accuracy were disturbed by the presence of the other electronic devices used in 4DAR. Experimenting with equipment placement or electronic shielding may help, but this will require further study.

Figure 5-4 shows a TopCon HiPer Pro RTK-GPS rover and base unit being used to provide the positional data and the helmet mounted compass tracking gaze orientation. Note that a one-off calibration is performed at initialisation to correct for the offset between the rover unit and the HMD.

Figure 5-4 Prototype testing using an RTK GPS setup.

Figure 5-5 shows the results of the tracking system in operation, as viewed through the 4DAR interface. Here, a simple geo-located 3D model of a building is being overlaid on the corresponding real building at the city north campus, University of Wolverhampton, UK. Note the correct perspective projection of the virtual model that is achieved through the correct calibration of the virtual viewpoint in relation to the physical camera.

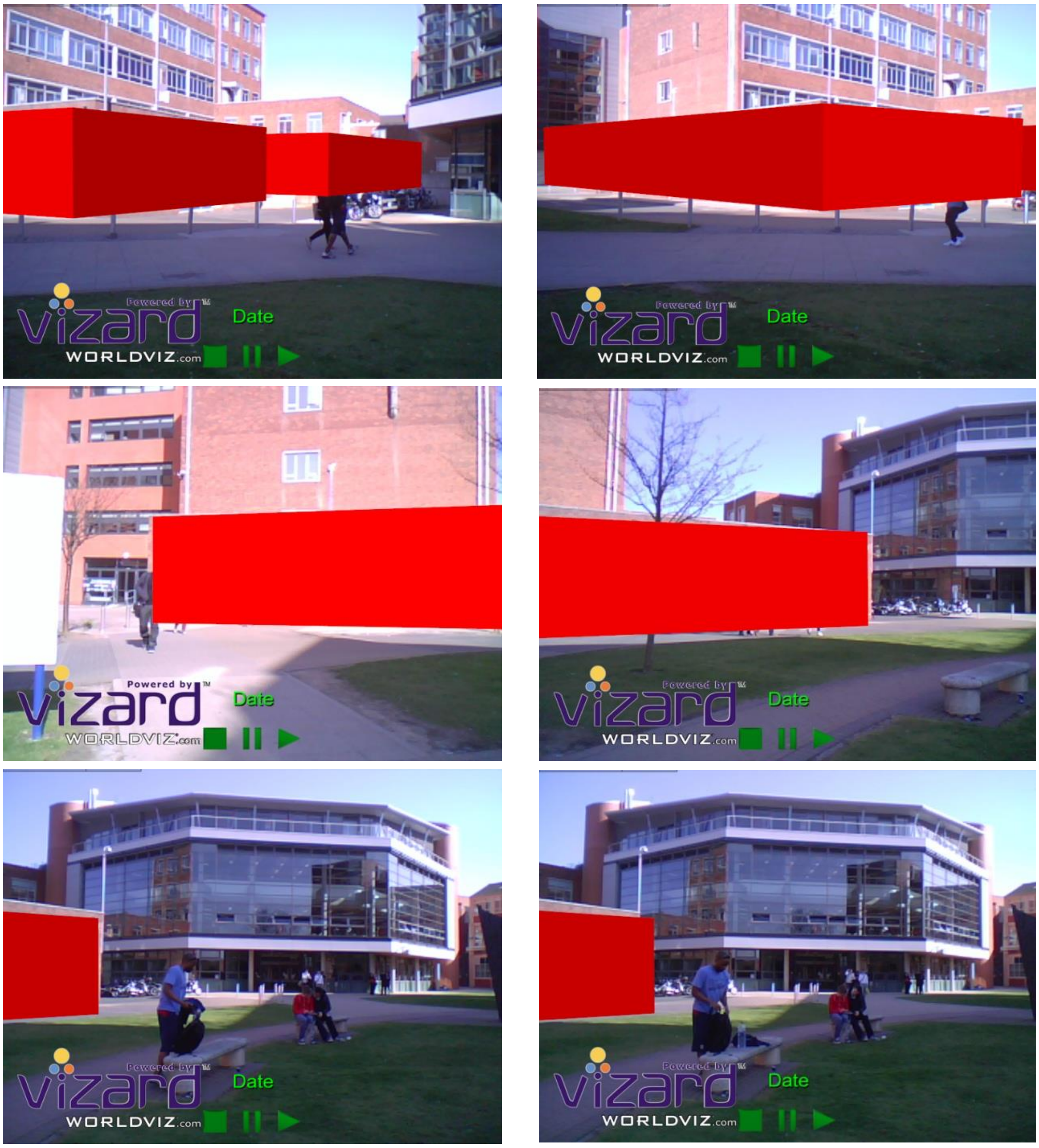


Figure 5-5 Testing tracking setup with simple geo-located 3D model

5.3.2 Operational Concepts

4DAR employs a single Graphical User Interface (GUI) for visualising and manipulating a building model in an outdoor Augmented Reality (AR) setting. The main operational functionality of the implemented prototype is carried out through the three python modules Controller, Model and View (Figure 5-2). Two further python scripts control serial connection and data retrieval from the GPS and Compass equipment, while one final script contains the HTML code that initialises the JavaScript calendar widget.

The Controller module first prompts the user to import the geo-located OpenSceneGraph (OSG) 3D model and the original IFC file into the system. Concurrently, the View module connects to the tracking equipment, head mounted display and video camera to enable immediate contextual visualisation of the 3D model. A reference to the 3D model object is then passed to the Model module along with the IFC file which is loaded into the IFCsvr object. In a separate thread, data is iteratively extracted from the IFC file and associated with the 3D model elements. Once an individual building element has been synchronised with its IFC object, the user can assign dates for its construction; however menus offering selection by object type or building storey are only populated once the synchronisation process is complete. See Appendix 1 for further information, screenshots and operational flowcharts.

Once all initial processes have been completed, callback routines in the Controller Module watch for user initiated events, i.e. event driven. These events, such as picking a 3D object or selecting a menu entry, are in turn component parts of the planning tasks undertaken within 4DAR, i.e. task oriented. This event driven, task oriented approach provides an open ended, non-prescriptive environment for construction planning. In this augmented space, the user is encouraged to contextually explore and interact with a building model towards the development and visualisation of schedule information.

To initiate the planning process, the user selects a building element directly, or group of elements from the selection menu. The Controller informs the Model of all picking events to enable it to keep track of current and previous selections. A null selection is also utilized to enable the user to deselect any selected items. The Model informs the View that elements have been selected and / or deselected so that it can adjust their visual state accordingly. Red shows the current selection set while objects are left green to signify they have been assigned to a schedule task. Each schedule task in 4DAR is presumed to be a construction type activity therefore each task name is derived from the name of the current selection set.

The right mouse button displays a pop-up menu at the cursor with several options available including displaying the calendar widget used to assign dates to tasks. When a date range is submitted from the calendar widget, the task name, the dates and the currently selected building elements are added to a nested data container maintained by the Model. Once at least one task has been defined, the same schedule data container can be accessed to enable 4D visualisation of the construction schedule. The user can then asses the constructability and validity of the schedule and alter the dates assigned to tasks accordingly by reselecting the object, or group of objects and redefining their construction dates. Additionally, any schedule data already present in the IFC file can be loaded into the 4DAR prototype system where it can be managed, viewed and edited in the same manner as user created data. Furthermore, complete or partial schedule data can be saved back to the IFC file and later loaded back into the system to facilitate its visualisation and / or alteration. This process of defining and redefining task dates and viewing the resulting 4D simulation enables an open-ended iterative visual approach to scheduling to be employed within the 4DAR prototype.

5.4 CONTROLLER MODULE

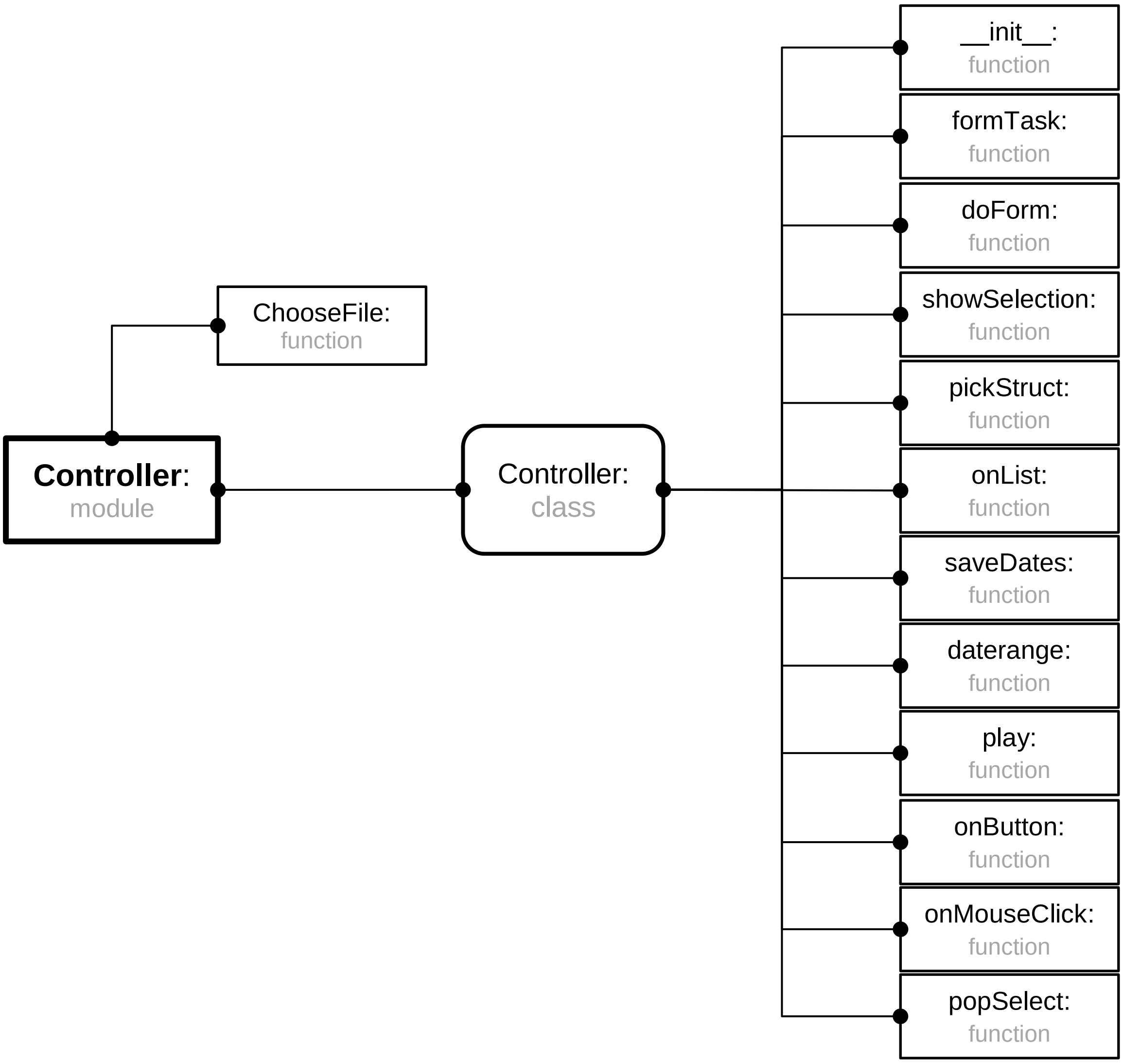


Figure 5-6 Structural Diagram of Controller Module

As the top-level python script in the implemented system, the Controller module is responsible for controlling the program flow as well as managing all user-system interactions within 4DAR. All functionality relating to the capture of information from the GUI and 3D model interactions is encapsulated by this module which is also responsible for notifying the other modules of the implications of the user interaction.

5.4.1 Controller Class

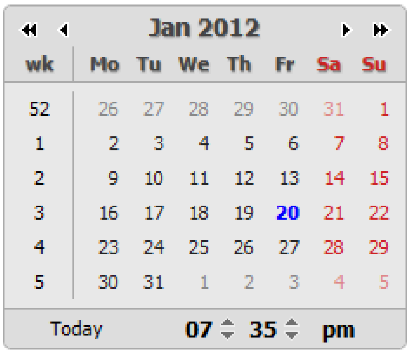
This class represents the user's entry point into 4DARs augmented planning environment. When the Controller class is instantiated, it prompts the user to import the files required by the system. This is achieved by calling the module level `ChooseFile()` function which opens a standard operating system "open and save" dialog window to allow the user to browse directories and import files. This function is called twice by the constructor, or `__init__()` method of the instantiated class with the dialog filtered each time to ensure only the correct file type can be selected for import. Firstly, an OpenSceneGraph 3D model file is required, followed by its corresponding IFC file. The 3D model object is added to the virtual world view before being passed to the scheduled `Model.modelSort()` function. The IFC file is passed to the `startIFC` method of the Model class which starts the IFCsvr ActiveX component and loads the IFC file into it.

Also initialised by the constructor are two instance attributes used by the scheduling engine during planning and playback operations. The `showBuild` list object is used by the 4D engine to hold the collection of objects that are under construction on a particular date. Similarly, the `whatType` attribute is used to hold the name of the current selection set, and is employed by the scheduling engine to provide the name for the current construction task.

`Controller.formTask` - This method of the Controller class is a function that controls the display and data capture from a JavaScript calendar widget embedded within a HTML form. For use during scheduling operations, the user is able to select a date range using the calendars GUI (Figure 5-7) to define the start and end dates for a particular task. To enable these date strings to be used by `Controller.daterange()`, they are converted to python `datetime` objects using the `datetime.strptime()` method. The selected dates are then passed to two separate functions within the Model class. The `Model.saveModelDates()`

function associates the chosen dates with any selected objects while `Model.markerDates()` keeps track of the earliest start date and latest finish date defined within the current schedule. Additionally, a call to the method `showSelection(current_task)` updates the on-screen display when dates have been assigned to a task.

The calendar object is initialized through a separate module file which is imported by the Controller module at initialization. This calendar module file contains the HTML form and JavaScript code that define the attributes that govern the appearance and mode of operation of each JSCal2 instance created. Two Vizard module libraries are employed by `Controller.formTask()` to enable the use of this DHTML technology within 4DAR. The `vizhtml` module provides the ability to embed HTML forms within the graphics window and collect submitted data. The `viztask` module provides a non-blocking method for waiting for the form submission using lightweight microthreaded tasks that are scheduled using Python's generator syntax.



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wk	Mo	Tu	We	Th	Fr	Sa	Su
52	26	27	28	29	30	31	1
1	2	3	4	5	6	7	8
2	9	10	11	12	13	14	15
3	16	17	18	19	20	21	22
4	23	24	25	26	27	28	29
5	30	31	1	2	3	4	5

Today 07 35 pm

Figure 5-7 The JSCal2 calendar widget

`Controller.doForm` **-** The sole purpose of this function is to schedule a task that executes the `formTask()` generator function. This is achieved by wrapping a `viztask.schedule()` function call to `Controller.formTask()` in a Controller class method. Constructing the task scheduling in this way enables the calendar widget to be called by an instance of this method whenever a specific GUI event occurs.

`Controller.showSelection` – This method provides a single function for communicating the name of the current selection set to a text container object controlled by the View module. Accepting single or group selections, `showSelection()` uses a method of the Model class to assert the presence of the current task (selection set) within the schedule. If it is present, then the start and end dates for that task are retrieved and added to the string sent to the View for display.

`Controller.pickStruct` **-** The `pickStruct()` method supports natural interaction with the visual building model by providing a picking routine that enables the user to select individual 3D elements within the model. Additionally, this function also reacts to a null selection (clicking on nothing) to enable deselection of any individual or multiple objects that are currently selected. The `viz.pick()` command is employed from the standard Vizard library module which returns the `<node3d:geometry>` object selected by the user and also gives access to the attributes added to each node in the scene graph during the initialization process. As the Controller is only responsible for capturing user interaction information, the selected `<node3d:geometry>` object is passed to the `Model.objSelect()` function which provides a unified method for managing all types of object selection within 4DAR. Additionally, the task name variable, `whatType` is updated with the current selection set name, and then sent to `showSelection()` to update the GUI information.

`Controller.onList` - This Controller class method captures selection menu interactions where users can select groups of objects based on their type or by their relationship to the proposed building. The menus referred to by this function only become available to the user once the initialisation process has been completed. At this point, selected IFC information becomes accessible within 4DAR as attributes of the 3D model elements and is used to populate the drop down menus alluded to by this function. A partner function to `Controller.pickStruct()` uses a callback mechanism that is triggered by a `viz.LIST_EVENT`. It also passes the user interaction context to the unified selection control method, `Model.objSelect()` and updates the task name variable with the name of the menu selection, passing this to `showSelection()`to update the GUI.

`Controller.saveDates` - Facilitating the use of the IFC file as a repository for the schedule information encourages a more centralised and reductionist approach to construction documentation. `Controller.saveDates()` calls the `Model.saveAttributes()` function which in turn controls methods in that modules' `IFC()` class to add the schedule information back to the underlying IFC file. This process involves the manipulation of the IFCsvr automation object which blocks the main thread of the Vizard application. Therefore, the `viz.Director()`Vizard function is employed to schedule the ActiveX object to run asynchronously in a separate operating system level thread.

`Controller.daterange` – The purpose of this class method is to enable iteration over a range of Python `datetime.date()` objects and is employed as an enabling function by `Controller.play()`. Implemented as a memory efficient generator function, `daterange()` enables iteration over a sequence of dates without the need to construct the sequence as a list in advance. Mirroring the manner in which Pythons' built-in `range()` function iterates over a sequence of numbers, this method operates on a range that is defined by two passed-in `datetime.date()` objects in this manner: `daterange(start,stop,step_days=1)`, where `step_days=1` defines a default increment for the iteration if none is passed in.

`Controller.play` – Implemented using Vizard tasks, this method provides 4D playback functionality within 4DAR. Utilising the `Controller.dateRange()` function, this method iterates over a sequence of dates defined by the first and last dates in the schedule. With no knowledge of scheduled tasks or the elements in the 3D model, `play()` leverages functions within the Model and View modules to provide the ability to visualise a 4D simulation in real time.

Called from a Controller method that captures GUI interactions, this method is passed a collection of objects, flags and variables that enable it to iterate over a specified date sequence. Specifically, `play()` expects 6 individual pieces of information; `wait` and `step` are two variables that define the speed of playback and the size of the playback step (playback level of detail) respectively, `firstDate` and `endDate` are imported module level variables that hold the schedules' beginning and end dates, while `playing` and `paused` are flags that are used to hold the state of current 4D playback. Additionally, the current date of a running 4D simulation is held internally by this function in the local variable `playDate` to enable a paused playback to be restarted from the correct date (see Figure 5-9).

`Controller.onButton` – This method of the Controller class is responsible for reacting to user interaction with the on-screen 4D player controls. A callback mechanism that watches for a `viz.BUTTON_EVENT` is initialised in the main body of the script at run time (Figure 5-8). Once activated, the callback returns the button object that has changed state and the state it has changed to, which is presented as either `viz.DOWN` or `viz.UP`.

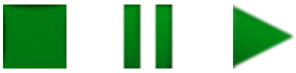


Figure 5-8 4D Playback Control Buttons

Every time `onButton()` is called, it gains access to the global variables `playDate`, `playing` and `paused` and reloads the `firstDate` and `lastDate` variables from the Model. If the play button is activated then all but the `playDate` variable are passed to the `Controller.play()` method by way of a `vizact.schedule()` call. Using tasks in this manner enables 4D simulation playback to be halted by killing the task that scheduled `Controller.play()` and thus removing it from the scheduler. The pause and the stop button both employ this same functionality; however manipulation of the global Boolean variables `playing` and `paused` differentiates between them in use and enables the `play()` function to react correctly to user interaction.

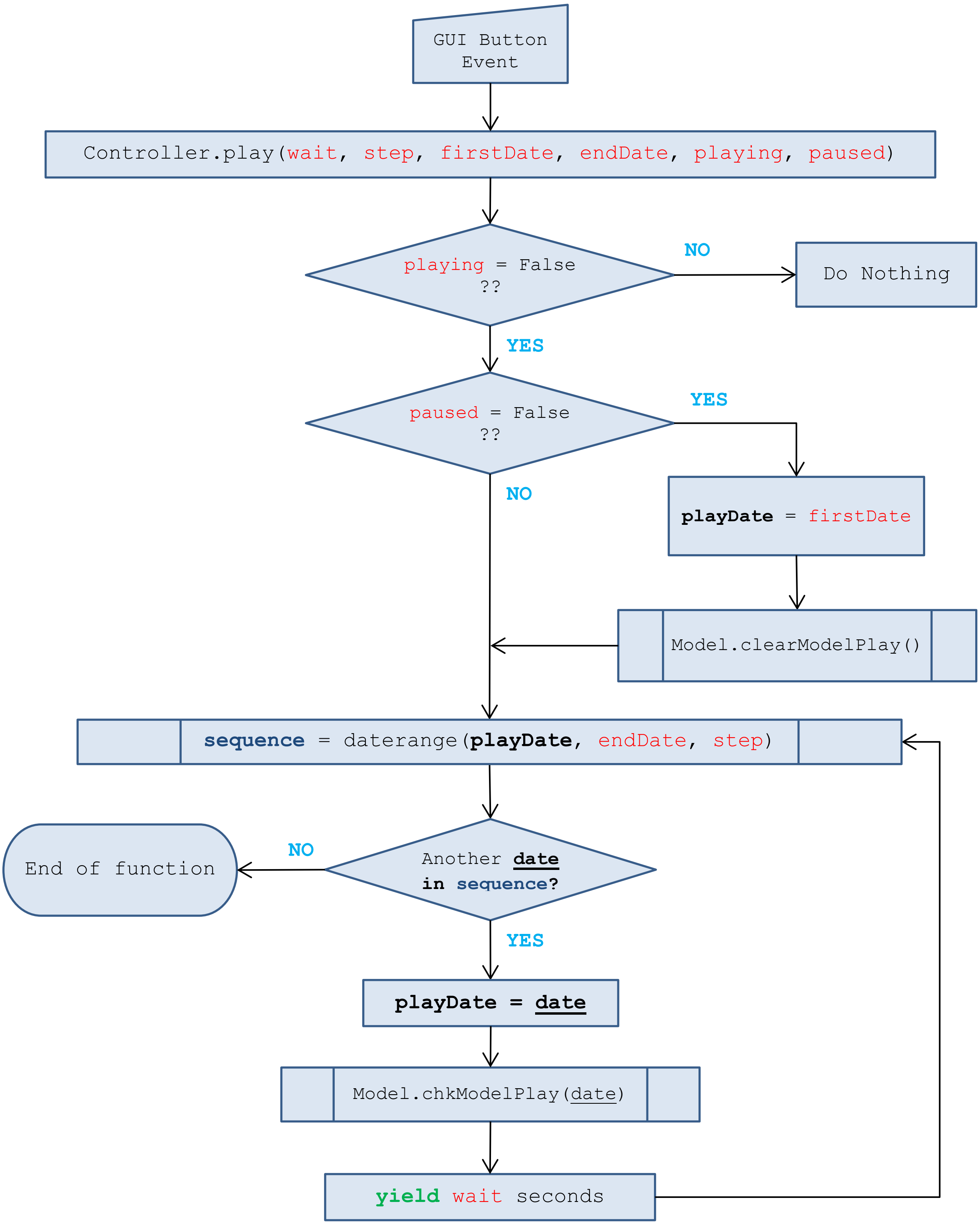


Figure 5-9 The play function logic

`Controller.onMouseClick` **–** Enabling a user to interact with 4DAR without the use of a keyboard is essential for the successful operation in the field. Using an air mouse enables intuitive input conventions to be utilised within an AR environment. Registered with a callback within the main body of the script, `onMouseClick()`enables custom responses to be attached to a mouse button event, `viz.MOUSEDOWN_EVENT`. Two conditions are then tested for, `viz.MOUSEBUTTON_LEFT` and `viz.MOUSEBUTTON_RIGHT`, which in turn initiate two different reactions. By default, the left mouse button is used for selecting items within the 3D window. This function extends this by attaching a `pickStruct()` method call to this event enabling intuitive interaction with the 3D model. The right mouse button is used to call a method of the View class, `popUp()`, which opens up a popup menu populated with options for displaying a calendar widget and IFC file I/O operations.

`Controller.popSelect` – As with the previous two class methods, this function is served by a callback mechanism that watches for a particular event, which in this case is a `vizpopup.MENU_SELECT_EVENT`. Capturing the popup menu selection object in the variable **`e`**, this function extracts the name of the selected menu item using the standard attribute dot notation, `e.item.name.` This is then checked by a series of conditional statements to provide the appropriate functionality, for instance initialising the calendar widget using an instance of `Controller.doForm()` or writing schedule information to a new IFC file using `Controller.saveDates()`. A second IFC submenu entry is greyed out by default; however when schedule data exists within the loaded IFC, this option becomes active. When selected, this option makes a `viz.Director` function call that runs `Model.readDates()` in a separate thread to stop the IFCsvr object from blocking the main rendering loop in Vizard.

As the top level python script in the 4DAR development, Controller is executed as the main module by the Python interpreter. Because of this, the special name "__main__" is automatically assigned to the modules special variable __name__ to signify that it is not being imported and executed by another script. Using this information, it is possible to add code to a Python module that is only executed if the script is run directly by preceding it with this conditional statement: ”`if __name__ == ”__main__”:`”. Using this standard Python approach, code was added to the end of the Controller module to enable it to function as a top level script. Specifically, this entails initialising global variables, registering the various callback mechanisms utilized by this module and starting the Vizard rendering loop.

5.5 VIEW MODULE

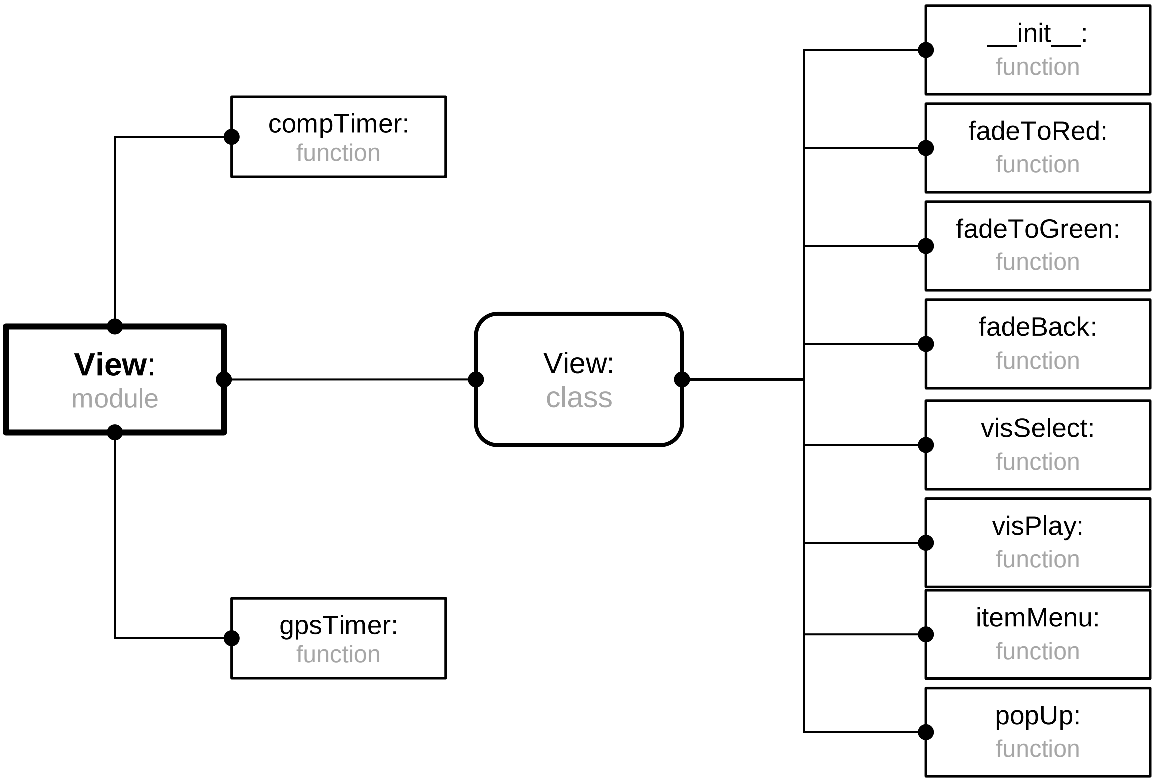


Figure 5-10 Structural Diagram of View Module

Following the Controller Module, the View constitutes one half of the user interaction layer in 4DAR. Controlling the initialisation of the graphical user interface and the visualisation of the underlying building model, the View controls the visual elements with which the user interacts. This module initialises the virtual camera, or viewpoint, based upon the intrinsic parameters of the real camera to enable registration between the video feed and the virtual content. Additionally, the positioning of the viewpoint must coincide with the user's position in the real environment; therefore this module also connects to the tracking equipment to link the viewpoint position and orientation to the tracking data.

Two module level timer functions are responsible for initialising and maintaining the connection with the RTK-GPS and Compass units, `compTimer()` and `gpsTimer()`. Accessing methods of the imported GPS and Compass Modules, they enable the acquisition of tracking data from the NMEA sentence strings output by the positioning units. Using individual timing loops in this way allows them to be set at the update rate for that particular piece of positioning equipment. This, in turn, enables the tracking data, and therefore the viewpoint position and orientation, to be updated asynchronously and independently of the Vizard rendering loop.

Imported by the Controller during the start-up process, the View initialises all GUI elements used within 4DAR. These elements include the on screen text containers, `showSelect`, `showEnd` and `showDate`, as well as the buttons for controlling the 4D playback functionality. Empty menu objects for the drop down selection menu are also defined at the module level, but are only populated once the Model has finished extracting the IFC information. The popup menu is initialised and populated during start up and available on the right mouse button as soon as the interface is up and running.

Positioned in the top right corner of the interface (see Figure 5-11), the multiline `showSelect` object is used to display both the current selection set during scheduling operations and the list of running tasks during 4D playback. The `showDate` object displays the current simulation date and is only used during 4D playback. Finally, the `showEnd` GUI object is employed only to display the names of completed tasks in green below the running task list.

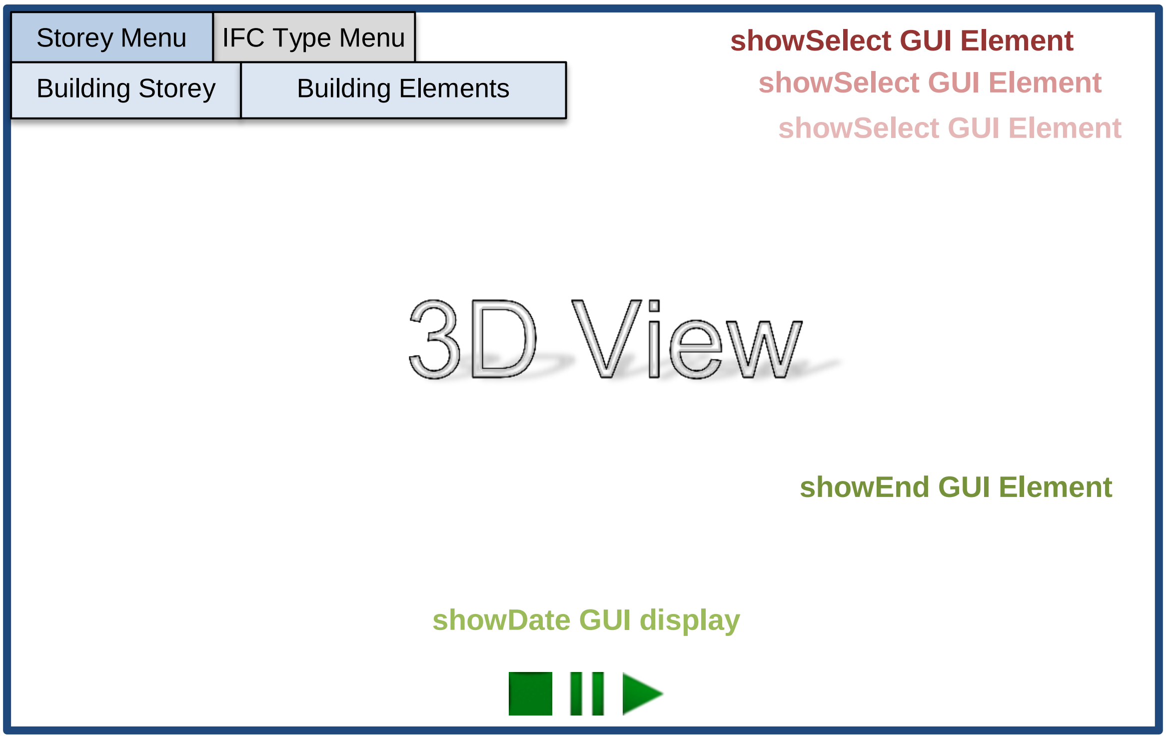


Figure 5-11 Diagram of GUI layout

5.5.1 View Class

This class provides methods for controlling the visual state of the 3D model and GUI elements during scheduling and 4D playback operations. It is also responsible for setting the viewpoint and initialising GUI components.

`View.fadeToRed` – This View class method is one of three helper functions used by `View.visSelect()` to change the appearance of 3D nodes. This and the following function, **`View.fadeToGreen()`** utilise Vizards' action library to temporarily change the colour of building elements to signify selection or addition to the schedule respectively. Using actions in this way means that the colour change can be defined in advance and then used and reused simply by adding the action to the 3D object, `<node3d>.addAction().`

`View.fadeBack` – This class method also employs the `vizact` action library to alter the appearance of a 3D node. By referencing the custom `.colour` attribute, one of several added to each 3D node during initialisation, this function is used to return an object to its original visual state.

`View.visSelect` – Utilised by the `Model.obSelect()` function, this method of the View class manages the visual appearance of objects that have been selected or deselected by the user. Informed by the Model when a selection event has occurred, `visSelect()` controls the visual state of current and prior selections concurrently or individually. Using default parameter values in the function header statement, `(info=None,lastOne=None)`, enables this function to be called with none, one or both of these possible selection events being passed in. For example, when a null selection event occurs, the `info` argument defaults to `None`. However, the `lastOne` argument may or may not contain an item to be deselected, depending on whether this is the first or a subsequent null selection.

When this function is called, a conditional statement first checks the `lastOne` parameter for an item that is being deselected by the Model. If one has been passed, the custom `<node3d>.scheduled` attribute reveals whether it has been added to the schedule. Nodes not added to the schedule are returned to their original colour, while those that have been scheduled are turned green. If a current selection has been passed to this function then it will be contained by the `info` parameter. Any `<node3d>` object within `info` is passed straight to the `fadeToRed()` method to provide the user with visual feedback of the current selection.

`View.visPlay` – This function accepts several keyword arguments and is called by the Model during 4D playback to manage the visual state of 3D model components. The header statement takes the form, `func(**kwargs)`, in which the special syntax "`**`" allows `keyword:value` dictionaries of arbitrary length to be passed to a function. This approach provides a common interface for calling the function, `func(keyword = value)`, even if functionality is extended in response to future use requirements. In this case, there are three possible keywords that can be employed when calling this function during 4D playback, "start", "end" and "clear".

Using the standard Python dictionary syntax, this function checks the passed in `kwargs` dictionary for keywords, extracting the `<node3d>` object paired with it and manipulating its appearance accordingly. The keyword "clear" is used by the iterative function `Model.clearModelPlay()` to zero the alpha value of each child node passed to it thus rendering it invisible. The "start" and "end" keywords, however, are both employed by `Model.chkModelPlay()` to enable control of the visualisation of the construction schedule over time. A `<node3d>` object passed with the "start" keyword is made partially visible and is coloured green (`fadeToGreen()`) to signify it is under construction. Conversely, an object passed in with the keyword "end" is no longer under construction and is returned to its original colour (`fadeBack()`) and alpha value to signify the completion of that task.

`View.itemMenu` – Called once after system initialisation has finished, this class method populates two drop down selection menus initialised during start up with data mined from the IFC file. Using the `**kwargs` variable argument in the header enables this function to be passed two `defaultdict` dictionaries constructed by the Model during IFC synchronisation. Using `defaultdict(dict)` enables a nested dictionary to be constructed implicitly by defining a default factory for keys that have not yet been created, in this case another dictionary. The `typeDict{}` and `storeyDict{}` dictionaries are nested data structures that map 3D elements by either IFC type or building storey respectively, with a value list of associated 3D nodes for every entry of the inner dictionary (see Figure 5-12).

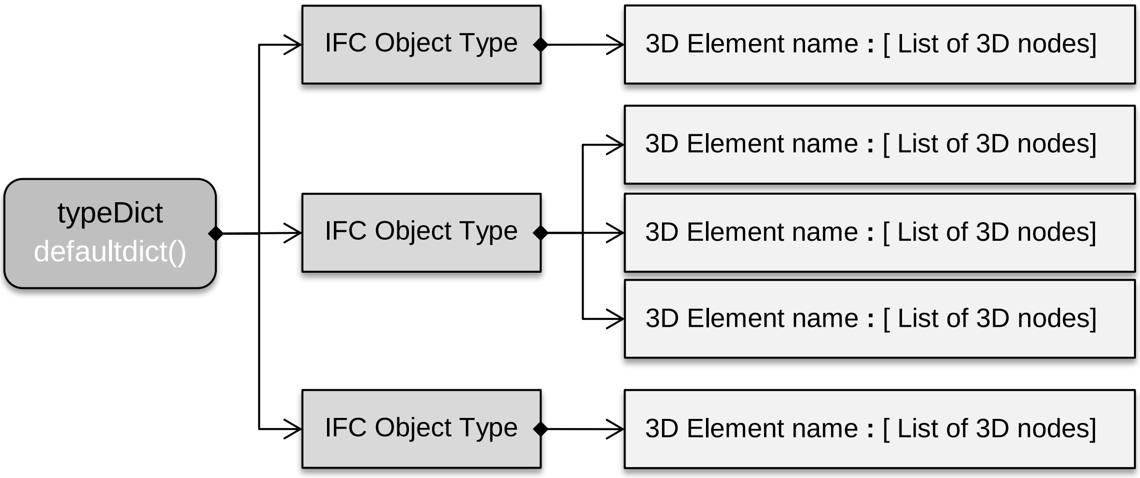


Figure 5-12 Nested dictionary container

A nested loop of the form, `for x in dict: … for y in dict[x]:`, enables menu construction that mirrors the structure of the data being represented (Figure 5-13), while the keywords `type` or `storey` indicate which data is being passed to the function. An additional menu object is added to the menus for every key in the outer dictionary, or `x in dict`. Items are then iteratively added to these new menu objects for every key of the nested dictionary, `y in dict[x]`. Only the first and second level data is required from either dictionary when populating these selection menus, the lists of associated `<node3d>` objects associated with each `dict[x]` are used during object selection and are not required here.

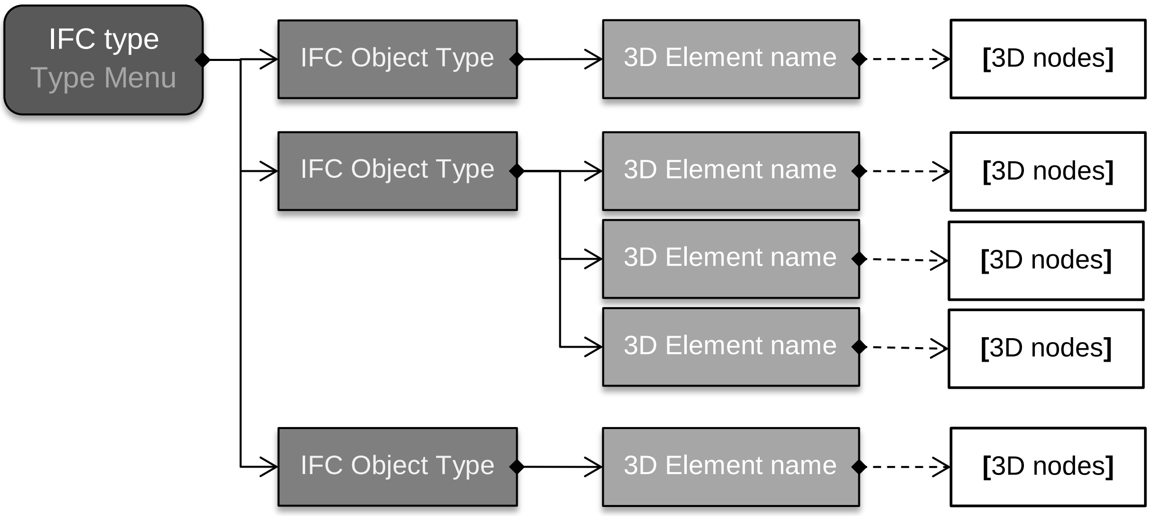


Figure 5-13 Drop down menu structure

`View.popUp` – The sole purpose of this class method is to provide an interface to the popup menu, in that it hides the function `vizpopup.display(defined menu object)` in a simple `View.popup()` method call. This enables the Controller to trigger the popup menu via a mouse button event without knowledge of the type of menu being used.

5.6 MODEL MODULE

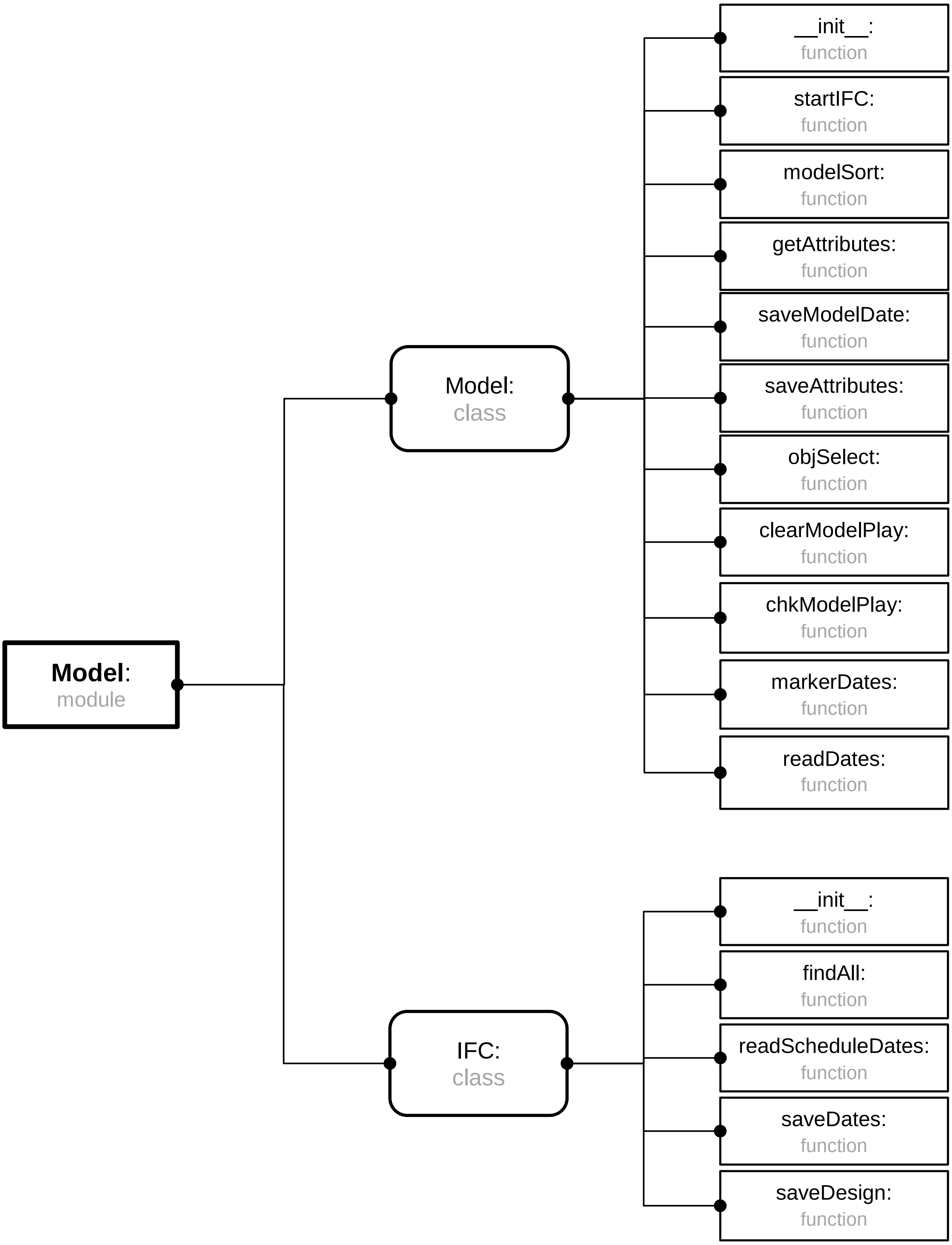


Figure 5-14 Structural Diagram of Model Module

This module contains all the operational functionality needed to manipulate the underlying scene graph and the corresponding IFC file towards the creation of a unified building model. This augmented 3D model is central to the operational functionality of 4DAR and is created by the Model using information harvested from the IFC file. Loosely coupled with the Controller, this module is notified only when a user interaction event occurs. The Model then alters the underlying model accordingly and informs the View so that the 3D visualisation always represents the current state of the domain model.

Called by the Controller module, the Model first defines a module level data container. This deeply nested container object is defined as a `defaultdict` with an anonymous function as its default factory: `lambda:defaultdict(defaultdict)`. This enables the *a priori* creation of a three-deep nested dictionary called `scheduleDict{}` which is iteratively populated with schedule tasks, each with a set of dates and a list of associated building objects (Figure 5-15). Being implemented at the module level in this way enables the `IFC` class to have easy access to `scheduleDict{}` when reading or writing schedule information to and from the IFC file.

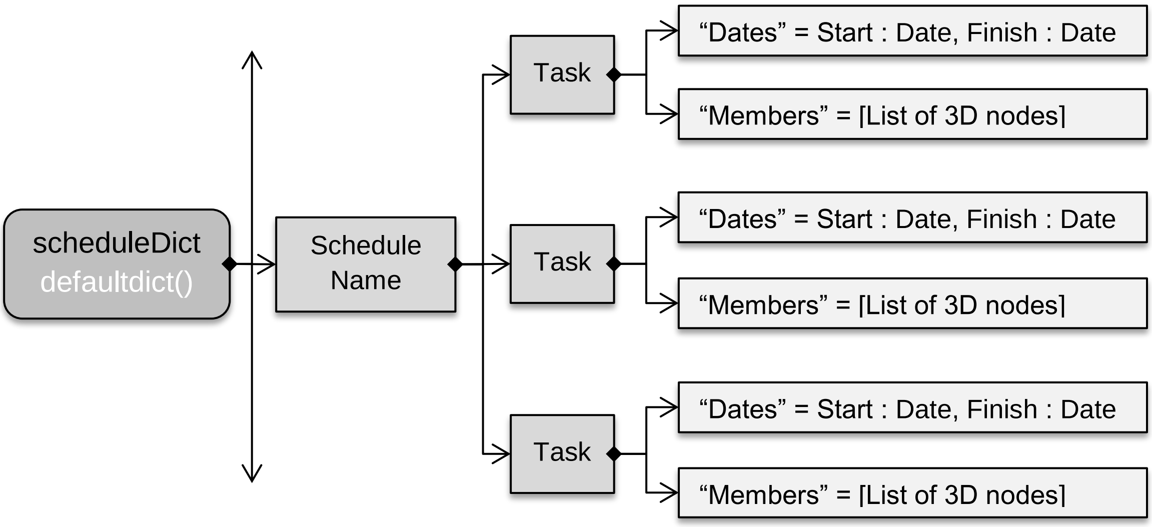


Figure 5-15 Diagrammatical concept of the nested schedule data container

Below is the coded structure of the `scheduleDict{}` container (Figure 5-16) which is interrogated by the Model and IFC classes using the standard Python dictionary syntax. For example, to access the start date of a construction task a request is made in the following form, `scheduleDict[scheduleName][task][“Dates”][“start”]` while `scheduleDict[scheduleName][task][“Members”]` returns the list of associated 3D nodes.

```
scheduleDict{scheduleName:{taskName:{“Members”:[List_Of_3D_Nodes],
“Dates”:{“start”:00/00/00, “end”:00/00/00}}}}
```

Figure 5-16 Structure of nested Schedule Dictionary

The variable `scheduleName` is also created and defined at module level from the computer account name and the current time and date. This string is used as a unique schedule name for each run of the implemented application. Finally, the two variables `firstDate` and `lastDate` are used to hold the earliest and latest dates in the current schedule. Initialised at the top level of the Model module, they are used by the `Controller.playDate()` function during 4D playback.

5.6.1 Model Class

Instantiated by the Controller class when the application starts, the __init__ method of this class itself creates an instance of the Viewer class to enable it to inform it of state changes to the underlying model. Other variables and objects used by this class are initialised here, including `typeDict{}` and `storeyDict{}` which are used to populate, and later support object selection from, the drop down menus. These nested dictionaries are of the type `defaultdict(dict)`, where the default factory produces a standard python dictionary object (Figure 5-12).

`Model.startIFC` – Called by the Controller at start up, this Model class method instantiates the `IFC` class to start the IFCsvr.R300 ActiveX object to which is passed the currently loaded IFC file. The `IFC` class is not accessed directly by other modules; instead the Model class provides methods which effectively provide an interface to the functionality provided by that class.

`Model.modelSort` – This method of the Model class creates the underlying unified building model used by 4DAR from the 3D model of the proposed building and its corresponding IFC file. Central to the operational functionality of the implemented system, the unified building model is produced by adding extra attributes to every node in the 3D model and populating them with the corresponding IFC information.

Gaining access to a child `<node3d>` object in the 3D model requires prior knowledge of that child nodes name. Using resources loaded by the user at run time means that this information cannot be known in advance. Consequently, this function first retrieves and then sorts a list of the names of all child nodes beneath the root `<node3d>` object in the scene graph. Looping over this sorted list enables this function to traverse the scene graph using the Vizard method `<node3d>.getChild(`*`Name`*`)`, which returns the child node *Name* as an object. These objects are then instantiated to enable this method to define the extra object attributes utilised by the 4DAR system. These attributes can be split into three categories:

1) Attributes that hold information gleaned from the 3D model:

  - **`<node3d>.colour`** – Stores the original colour of the node and is used as a reference to which the node can be returned.

- **`<node3d>.Alpha`** – Stores the original alpha value and, like the above attribute, is used as a reference to which a node can be returned when its visual state has been altered.
- **`<node3d>.Name`** – This attribute provides a truncated version of the full node name. Splitting the original name string to remove the Tag number (see below), renders a generic type name that refers to the building element that the node represents.
- **`<node3d>.LongName`** – Holds the full, and unique name of the node which was retrieved as part of the sorted list at the beginning of this function.
- **`<node3d>.Tag`** – The Tag number is an `IfcElement` attribute that enables unique identification of an IFC object and is extracted from the end of the node name. For example, a door in an OSG file created from an IFC file presents with the full name, `Single-Flush 0915 x 2135[158746]`, the number between the square brackets is the Tag number, with the generic `.Name` attribute being assigned everything else. This `.Tag` attribute is used when synchronising a `<node3d>` object with its corresponding `IfcObject`.

2) Attributes that hold information extracted from the IFC file:

- **`<node3d>.p21id`** – This attribute holds the line number at which the IFC object occurs within the IFC file. This unique identification number is used as a reference to a particular IFC object when saving schedule information back to the IFC file.
- **`<node3d>.guid`** – This attribute is populated with the unique Global ID of the IFC object referenced by the current 3D node.
- **`<node3d>.TypeOf`** – The information held by this attribute is the object type of the IFC object referenced by the current 3D node. It is used during

menu creation to categorise items by their IFC type, for example `IfcDoor`, `IfcWallStandardCase` or `IfcSlab`.

- **`<node3d>.Storey`** – This object attribute contains the building storey or storeys on which a building element occurs. Because some objects like staircases and exterior walls fall over multiple storeys, this attribute is implemented as a list to enable multiple storeys to be referenced.

3) Attributes that are used internally by the scheduling engine:

- **`<node3d>.taskName`** – Defined initially as an empty string, this attribute will hold the name of the task to which the object is associated.
- **`<node3d>.scheduled`** – Initially set `False`, this Boolean attribute flags an object's membership in the current schedule.
- **`<node3d>.selected`** – Also initialised as a negative Boolean, this self-explanatory attribute demonstrates whether the object is part of the current selection set.

Once the object attributes have been defined, the data that is required to populate both the attributes in category two and the drop down selection menus is recovered from the IFC file. Using the `.getAttributes()` method to call a method of the `IFC` class, a Vizard task is employed to schedule the method call in a Director function and wait for the returned IFC data in a separate thread. The returned data is then unpacked directly to the category two attributes of the current object. The dictionary containers `typeDict{}` and `storeyDict{}` can now be populated using selected new attributes of each 3D object in the scene graph. The `typeDict{}` container (Figure 5-12) provides a list of 3D objects sorted by building element type and categorised by IFC object type and is constructed by looping over each `<node3d>` object like so:

```
typeDict[obj.TypeOf][obj.Name].append(obj.LongName).
```

Similarly, the container object `storeyDict{}` provides a list of 3D objects sorted by building element type which are then categorised by building storey. On completion, these two dictionaries are passed to the `View.itemMenu()` function where the two drop down selection menus are populated in relation to the dictionaries data (Figure 5-13). The following flow charts illustrate the operational functionality provided by this class method.

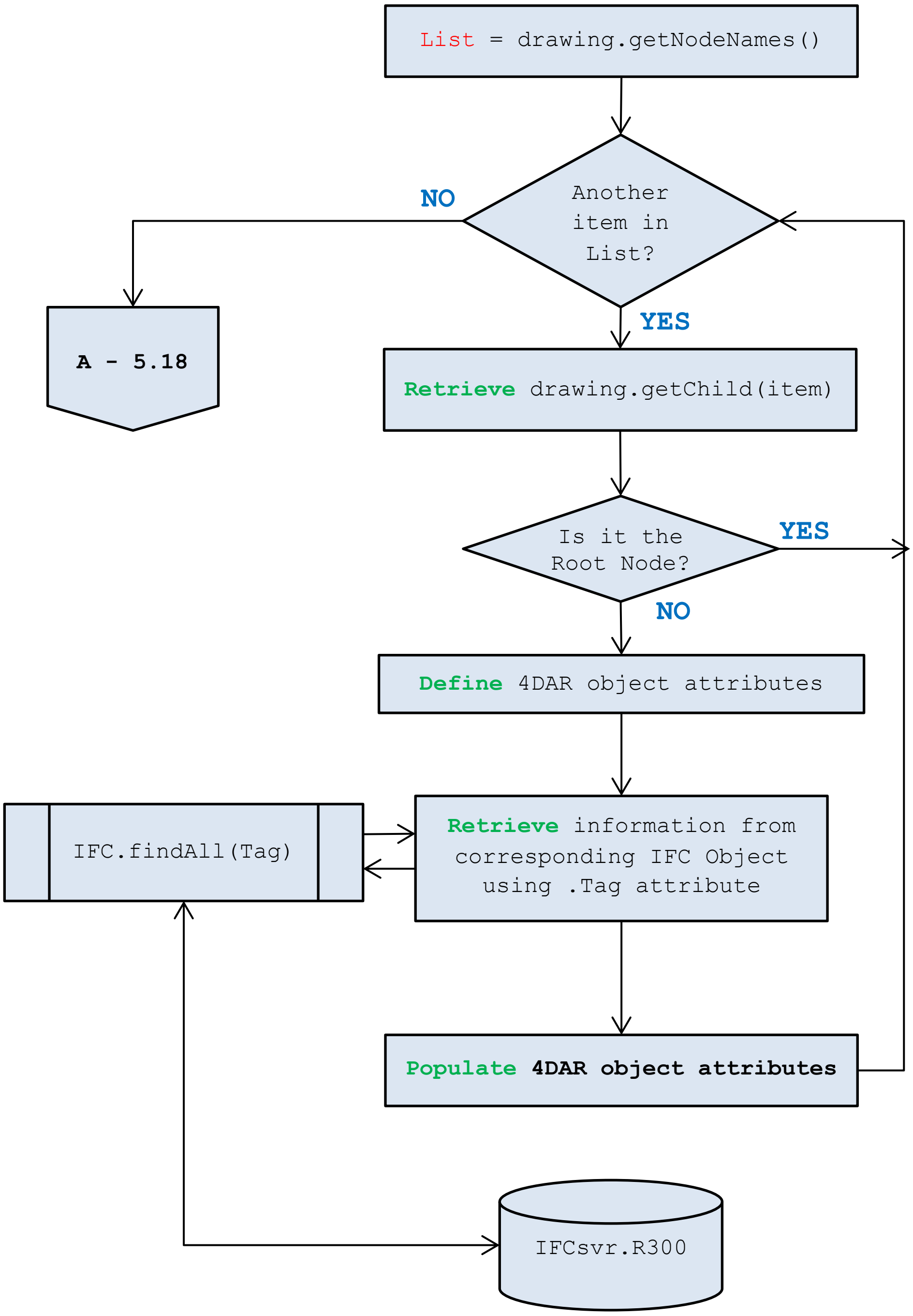


Figure 5-17 Menu initialisation and population routines

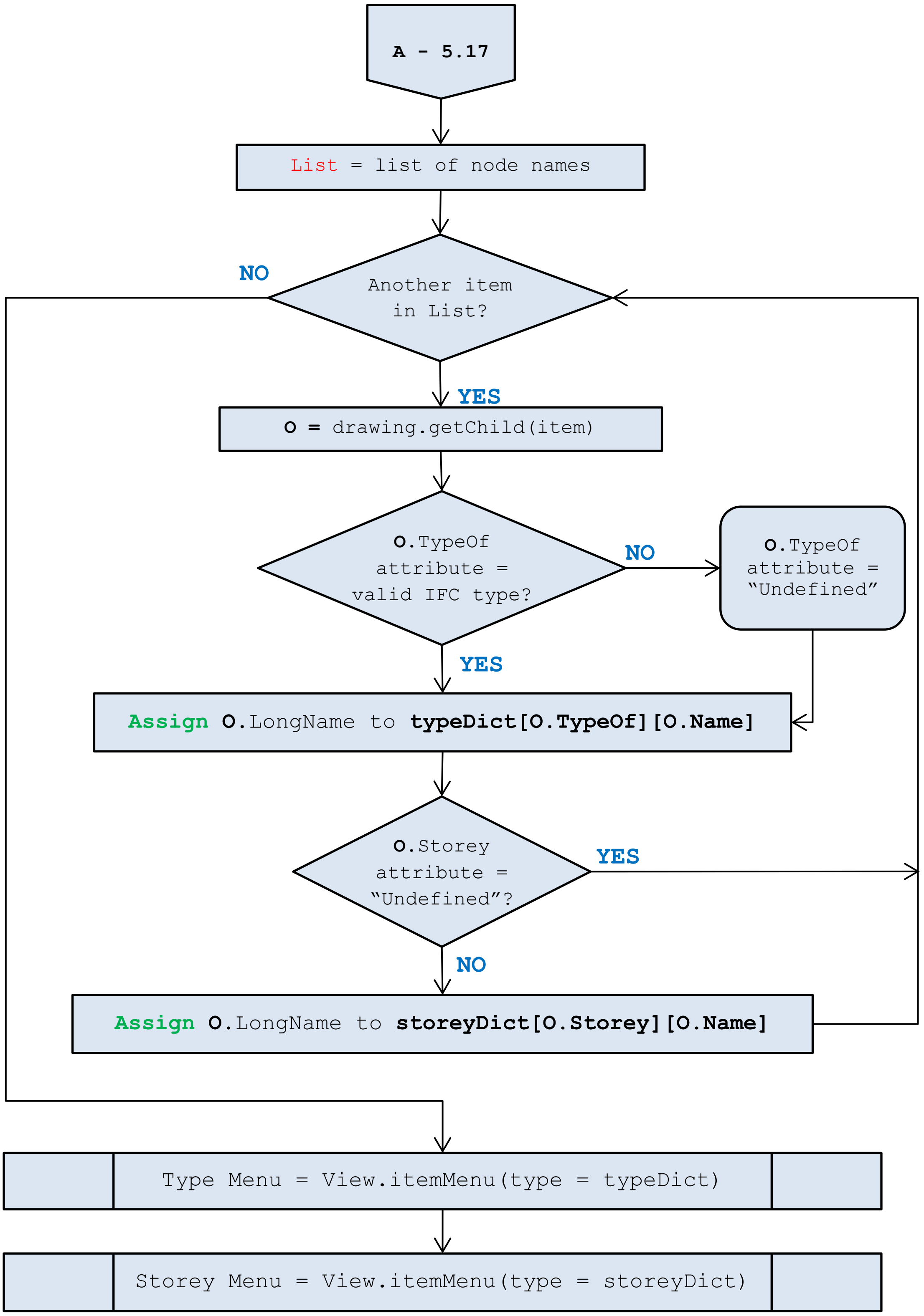


Figure 5-18 Menu initialisation and population routines continued

`Model.saveTaskDates` – This class method is called by the `Controller.formTask()` function upon submission of the selected date range. It then iterates over the scene graph checking each `object.selected` attribute for membership in the current selection set. If this attribute returns `True` then the `.scheduled` attribute of the object, and any of its children, is also set to `True`. Checking for direct children of individual nodes in this way means that compound objects like staircases or curtain walls can be scheduled and manipulated in the same way as individual nodes.

The object is passed to `View.visSelect()` using the `lastOne` keyword so that its visual state can be changed accordingly. When the `.selected` attribute is returned to `False` it signifies the object is no longer selected. The objects full name and the passed in start and end date objects are then added to the schedule dictionary in relation to the current task. Because each key in a dictionary must be unique, the dates are only added to the dictionary once when the task key is first defined; any successive attempt to add the same dates to that task will be ignored.

`Model.getAttributes` – Called in a separate thread, this function provides a convenient interface to the `IFC.findAll()` function. Scheduled by the previous `modelSort()` method, it passes on the value of the current objects `.Tag` attribute to enable its corresponding `IfcObject` to be found.

`Model.saveAttributes` – Employing two methods of the IFC class, this class method is also run in a separate thread using the `viz.Director()` method to prevent the main rendering loop being blocked. Called by a popup menu interaction event to enable the schedule to be added into to the IFC file, this method provides an interface to the `.saveDates()` and `.saveDesign()` IFC class functions.

`Model.chkSchedule` – This method call is utilised by `Controller.showSelection()` to check the current schedule for the presence of the selected item or items and returns the start and end dates of the task it is associated with. The name of the current selection is passed in by the Controller module and can refer to single or multiple items. Therefore, this method is implemented as three nested `for` loops iterating over `scheduleDict{}`so that both task names and node names can be examined.

Referring to the whole schedule, the outer loop runs only once. Although it would be possible to store multiple schedules in `scheduleDict{}`, manipulating multiple sets of schedule data is outside the scope of this project. The next loop iterates over the tasks in that particular schedule and is followed by a conditional statement that checks each task against the passed in selection name. If `True` then the start and end date objects are extracted from `scheduleDict[scheduleName][task][‶Dates″]` and returned to the calling function as a string using the `strftime()` method of the Python module `datetime`. When an object is scheduled as part of a group selection, its name will not appear as a task name. Therefore, the inner loop supports direct user - model interaction by iterating over the list `scheduleDict[scheduleName][task][‶Members″]` and returns the formatted dates if the objects name is present.

`Model.objSelect` – This class method provides a unified approach for managing all object selection events within 4DAR. Using the `**kwargs` parameter means this function can be passed a single object or group selections in the form `{kwarg:value}` using the keyword arguments `info` and `listName`. In addition, this approach permits this function can be called with no passed in objects if a null selection event occurs. If a single selection event has occurred then the selected object itself is passed by the `pickStruct()`function. However, if a group of objects have been selected then it is passed only the name of the current selection set. Additionally, this method stores currently selected items within the class level variables `lastInfo` and `lastNames` to enable them to be deselected when a new selection is made.

This function is divided into three sections that manage the different object selection options including a “click on nothing” null selection. The first two sections of `objSelect()` begin with a conditional statement that examines the passed in dictionary for the presence of a particular keyword. The function then uses exception catching to efficiently check both the `lastInfo` and `lastNames` variables for objects that are currently selected. It passes them, or any child nodes they parent, to `View.visSelect()` using the keyword “lastOne”, while setting the `.selected` attribute to `False`. This same process of checking for currently selected items and then deselecting them occurs in each section of `objSelect()` before the selection routines are processed and also when a null selection event is passed in.

The first section manages individual selection events and therefore watches for the keyword `info`. If this keyword is present then any currently selected items are first deselected (see above). The new selection object contained in the `info` parameter is then passed to `View.visSelect()` using the “info” keyword and its `.selected` attribute is set to `True` to complete the selection process. Following on, the objects `.taskName` attribute is here populated with the name of the current selection set, which in this case is the full node name. If an object is not assigned to a task as a result of this selection then the next selection event it is involved with will overwrite any previous task name. Finally, to enable this function to keep track of selection events, the `lastInfo` variable is populated with this new selection. The following section of this function manages IFC type and building storey group selections and which are both referenced using the single `listName` keyword. A conditional check is made for the existence of the keyword parameter `listName` and then previous selections are deselected. The paired value component of `listName` is then examined to ascertain if this represents a selection by IFC type or building storey. Depending upon the selection type one of the two dictionary objects, `typeDict{}` and `storeyDict{}` are traversed to check for the presence of the selection name. For example, a selection by building storey will return an element name in the second level of `storeyDict{}`. This, in turn, gives access to a list of associated 3D nodes which are added to a new selection set by setting each node’s attributes and informing the View. Once all objects have been processed the whole list of nodes is assigned to the `lastNames` variable which is traversed when deselected. The pseudo-code in Figure 5-19 illustrates the selection algorithms employed. The flow chart in Figure 5-20 clarifies the deselecting routine.

Single Selection

```
if “info” in kwargs:
  info = kwargs[“info”]
  RUN deselect routine
  temp = getChild(info)
  PROCESS temp node
  INFORM View temp is selected
```

Group Selection

```
if “listName” in kwargs:
  listName = kwargs[“listName”]
  RUN deselect routine
  for s in Dict:
    for ss in Dict[s]:
      if ss in listName:
        temp = getChild(ss)
        if temp has children:
          PROCESS each child node
          INFORM View child is selected
        else:
          PROCESS temp node
          INFORM View temp is selected
```

Figure 5-19 Selection Algorithms

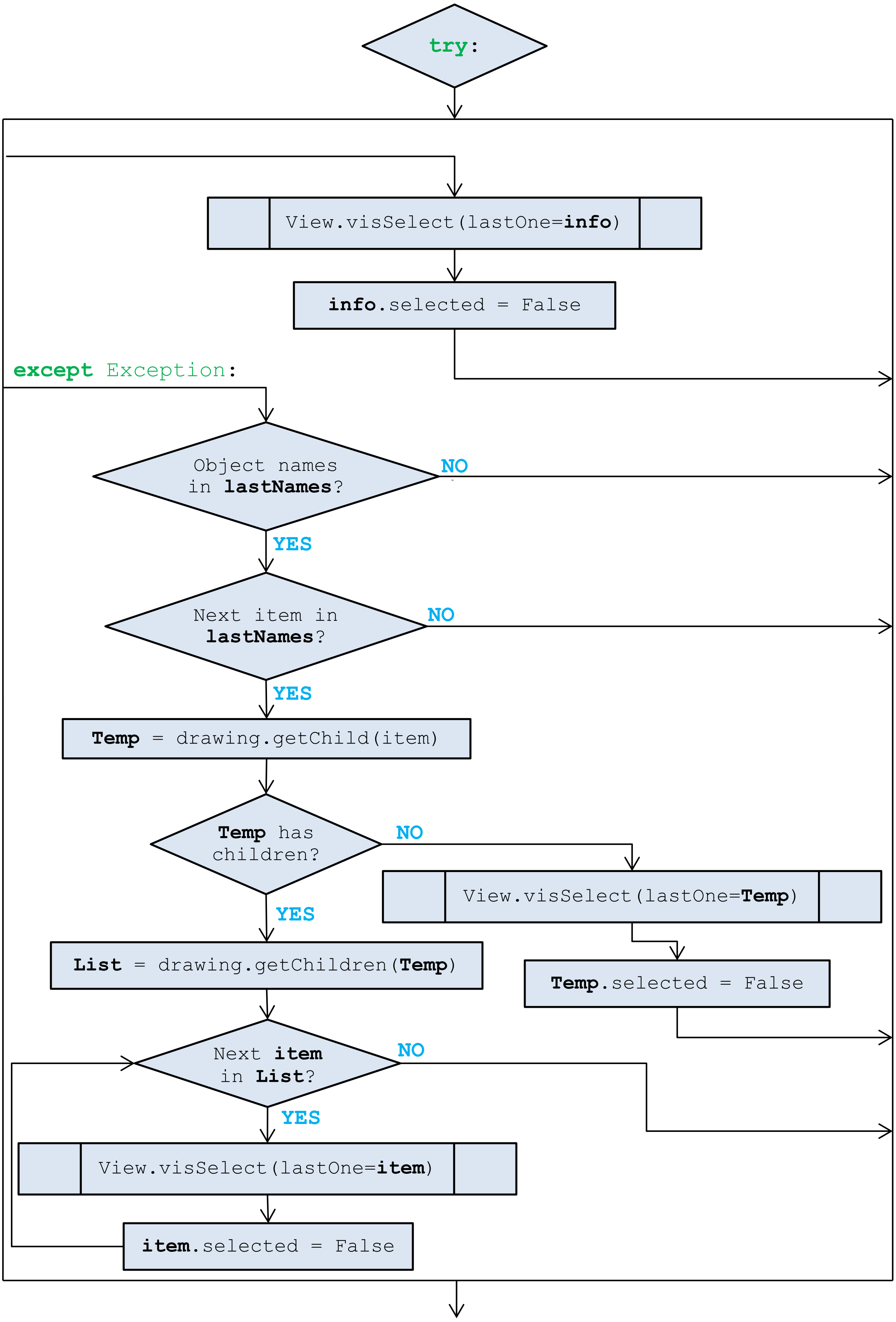


Figure 5-20 The deselect routine in objSelect()

`Model.clearModelPlay` – Making use of the `View.visPlay()` function, this class method provides an iterative approach to altering the appearance of nodes within the 3D model. It is called just before the `chkModelPlay()` method when the user selects to play a 4D visualisation. It then passes each child node in turn to the `visPlay()` method with the keyword argument “clear” until the whole model is invisible. Similarly, when the user selects the “stop” button from the 4D controls, this method is called and each node is passed to `visPlay()`. However, this time it is passed with the keyword “end” to signify that it should be returned to its original visual state.

`Model.chkModelPlay` – The purpose of this class method is to provide the backend Model support for the 4D playback functionality. Collecting the dates output by `Controller.play()`, this method queries `schedueDict`{} to ascertain the construction status on a given date. Information is passed to `View.visPlay()` at every iteration to enable it to correctly set the visual state of each child node in the 3D model. Furthermore, the current simulation date and a managed list of currently running tasks are passed to three different GUI text components for information display during 4D visualisation.

When a 4D visualisation is running, this function controls what information is displayed by the GUI based upon the current date and state of the underlying model. The `View.showDate()` GUI text container is informed of the current simulation date, while the GUI object that displays a finished task name, `View.showEnd()`, is initially cleared of any previous task names. The `View.showSelect()` is also used by this method to display the list of currently running tasks which is updated every time this method is called.

On each call, this method iterates over each task held in the current schedule to gain access to the start and end dates that have been defined for it. These date objects are then compared to the current date of the simulation to ascertain the status of that particular task on that date. If the simulation date corresponds to the start date for a task then its associated nodes are accessed via the list `sheduleDict[scheduleName][task][‶Members″]` to enable them to be processed accordingly. At each iteration over this list, the equivalent 3D node is retrieved from the model. A conditional statement then checks for that nodes task name in the class level list `showBuild[]`, and adds it if not already present. This list of task names is then sent to the `View.showSelect()` GUI object as a line delimited string using the Python method `‶\n″.join(showBuild)`. Once the GUI has been updated, the node object is passed with the keyword “start” to the `View.visPlay()` method to update the visual state of the 3D model.

Similarly, if the scheduled end date for a task is correspondent with the current simulation date then the “Members” list for that task is traversed and the 3D nodes are retrieved. However, if the task name for a node is present in `showBuild[]` then it is first removed before the list is sent to the View for display. This task name is then added to the `View.showEnd()` GUI component which displays the name in green to signify that this task has ended. Finally, the node object is passed to `View.visPlay()` using the keyword “end” which returns the node to its original visual state.

`Model.markerDates` – Informed by the Controller when task dates are defined, this class method keeps a track of the first and last dates of the whole schedule using the module level variables `firstDate` and `lastDate`. These variables, which are used by the `Controller.play()` function to define the extents of a 4D simulation, are compared to each new set of dates passed in and updated accordingly.

`Model.readDates` – Accessed via a popup menu entry that is only available when the IFC file already has a defined `IfcWorkSchedule` element, this class method provides the Controller with an interface to `IFC.readScheduleDates()`.

5.6.2 IFC Class

Employing a BIM centric approach to construction scheduling supports the streamlining and centralisation of construction documentation and is in line with current UK government policy. To this end, the IFCsvrR300 ActiveX or COM object is used to enable the implemented software tool to provide native support for IFC files. Utilising the win32com module, a component of the Pywin32 extension package, the automation objects interface is exposed in advance using early binding. This approach leverages the `win32.client.makepy` utility to create Python source code for the specified COM interface. This, in turn, enables the automation object in question to be manipulated from within a Python programming environment.

To create the necessary Python source code, the MakePy utility must be run from within the Python environment that requires the access to the automation object interface. Vizard version 4 is supplied with its own extended distribution of Python 2.7, therefore MakePy was run from the applications interactive prompt with the following code, where “DIRECTORY” is the path to the installation directory of the IFCsvr object.

```
>>> import win32com.client.makepy

>>> win32com.client.makepy.ShowInfo(‘DIRECTORY\IFCsvrR300.tlb’)
```

Figure 5-21 Generating Python source code for IFCsvr.R300 with the MakePy utility

This action causes the following to be output to the applications’ interactive window which in turn provides the means to access the created source code file, and therefore the automation object, from a Python script. The final two lines are inserted at the module level and executed when first imported by the Controller module.

```
IFCsvr
{B2173F4D-1371-4649-8554-310D6DC1734F}, lcid=0, major=1, minor=4
#Use these commands in Python code to auto generate .py support
from win32com.client import gencache
gencache.EnsureModule(‘{B2173F4D-1371-4649-8554-310D6DC1734F}’,0,1,4)
```

Figure 5-22 Output from MakePy utility

Instantiated by the Model class, the IFC class first initialises the class level variables, `existingSched`, `schedObj`, `taskCount` and `objCount`. An instance of the IFCsvr object is then created using the following code and the loaded IFC file is passed in. Note the use of “`objIFCsvr._FlagAsMethod`” which is needed to prevent Python from throwing a `TypeError` exception when the `OpenDesign` method is used on the ActiveX instance.

```
objIFCsvr = win32com.client.Dispatch(“IFCsvr.R300”)
objIFCsvr._FlagAsMethod(“OpenDesign”)
objDesign = objIFCsvr.OpenDesign(fileName)
```

Figure 5-23 Instantiating and initialising IFCsvr.R300

Finally, the constructor for this class checks the loaded IFC file, `objDesign`, for the presence of an `IfcWorkSchedule` object. If one is present then the user is enabled to load it into 4DAR by activating the popup menu entry that calls `Model.readDates()`.

`IFC.findAll` – Called by the Model for each object in the 3D model, this method uses IFCsvr methods to facilitate the synchronisation of selected IFC data between the physical file and the 3D model. The IFCsvr object provides methods for manipulating data at various levels within the BIM including collections of entities and attributes, as illustrated by the IFCsvrR300 Object Model (Figure 5-24).

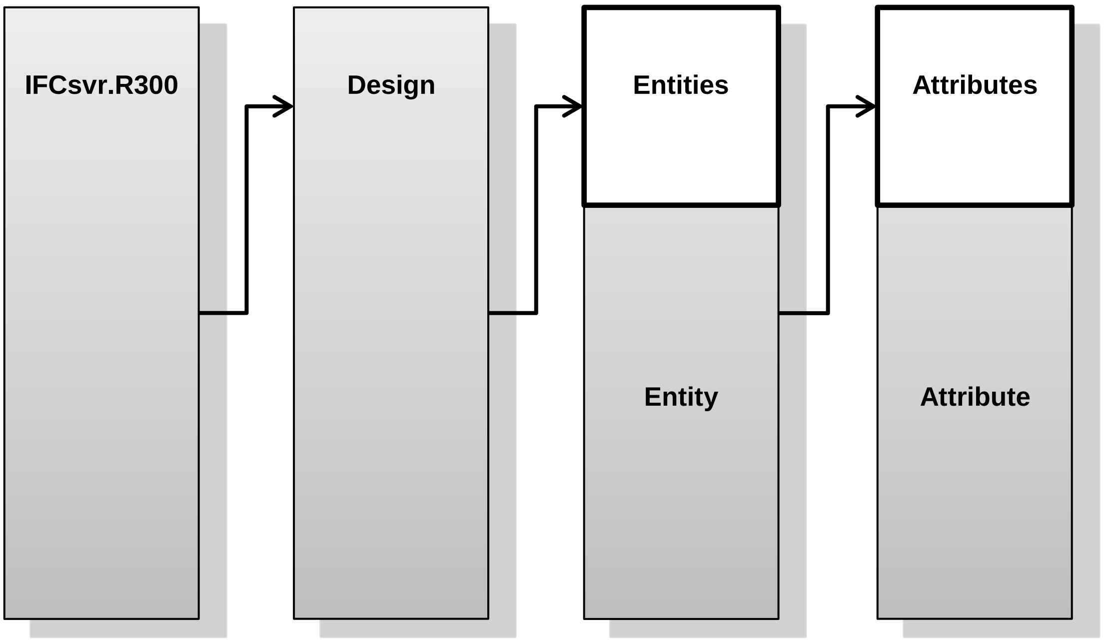


Figure 5-24 The IFCsvr.R300 Object Model

At each iteration of the `Model.modelSort()` function, this IFC class method is passed the number stored in a `<node3d>.Tag` attribute. Using this number, it is possible to locate an individual entity in the IFC using the `IFCsvr.Design` method `FindObjectsByValue()`. Individual Entity objects thus retrieved are queried using `IFCsvr.Entity` methods to retrieve its IFC Type, its item number within the IFC file (P21ID) and its Global Unique Identifier (GUID). All of these attributes are directly related to the IFC object itself and are accessed using direct methods provided by the IFCsvr, for example `<IfcObject>.Type` or `<IfcObject>.P21ID`.

The name of the building storey to which an object is associated can only be accessed through the INVERSE relationships of that object. The information for these so-called INVERSE attributes (reverse cross references between entities) are not stored in the IFC file itself, instead they have to be implemented using a certified ISO 10303 toolbox, such as IFCsvrR300. The `IFCsvr.Entity` object does not define its own INVERSE attributes. However, the `GetUsedIn(EntityType, AttributeName)` method can be used to return an `IFCsvr.Entities` collection object which references the INVERSE attributes described by the parameters used in the method call. To this, end the building storey for each building element is recovered by referencing the objectified `IfcRelContainedInSpatialStructure` INVERSE relationship of the building element in question.

`IFC.readScheduleDates` – This IFC class method is used to extract any existing schedule data from an IFC file and store it in the `scheduleDict{}` data container. Storing the imported schedule data in this manner enables the user to visualise it, manipulate it and extend it in the same manner as newly created schedule data. Furthermore, when an existing schedule is imported, its name is given to the `scheduleName` variable and it becomes the current schedule in 4DAR. Therefore, any changes or additions that are then made by the user will be saved back to the same schedule within the IFC file.

To enable the following `saveDates()` method to update an existing schedule, this method first retrieves and then stores the existing `IfcWorkSchedule` object in the class level variable `schedObj`. This function then iterates over each `IfcTask` object within the IFC file, accessing their scheduled dates and associated building elements via the INVERSE relationships `IfcRelAssignsTasks` and `IfcRelAssignsToProcess`, respectively. This relational information is then stored within the `scheduleDict{}` container under the retrieved schedule name and is appointed as the default working schedule for that session. Figure 5-25 illustrates the flow control for this class method.

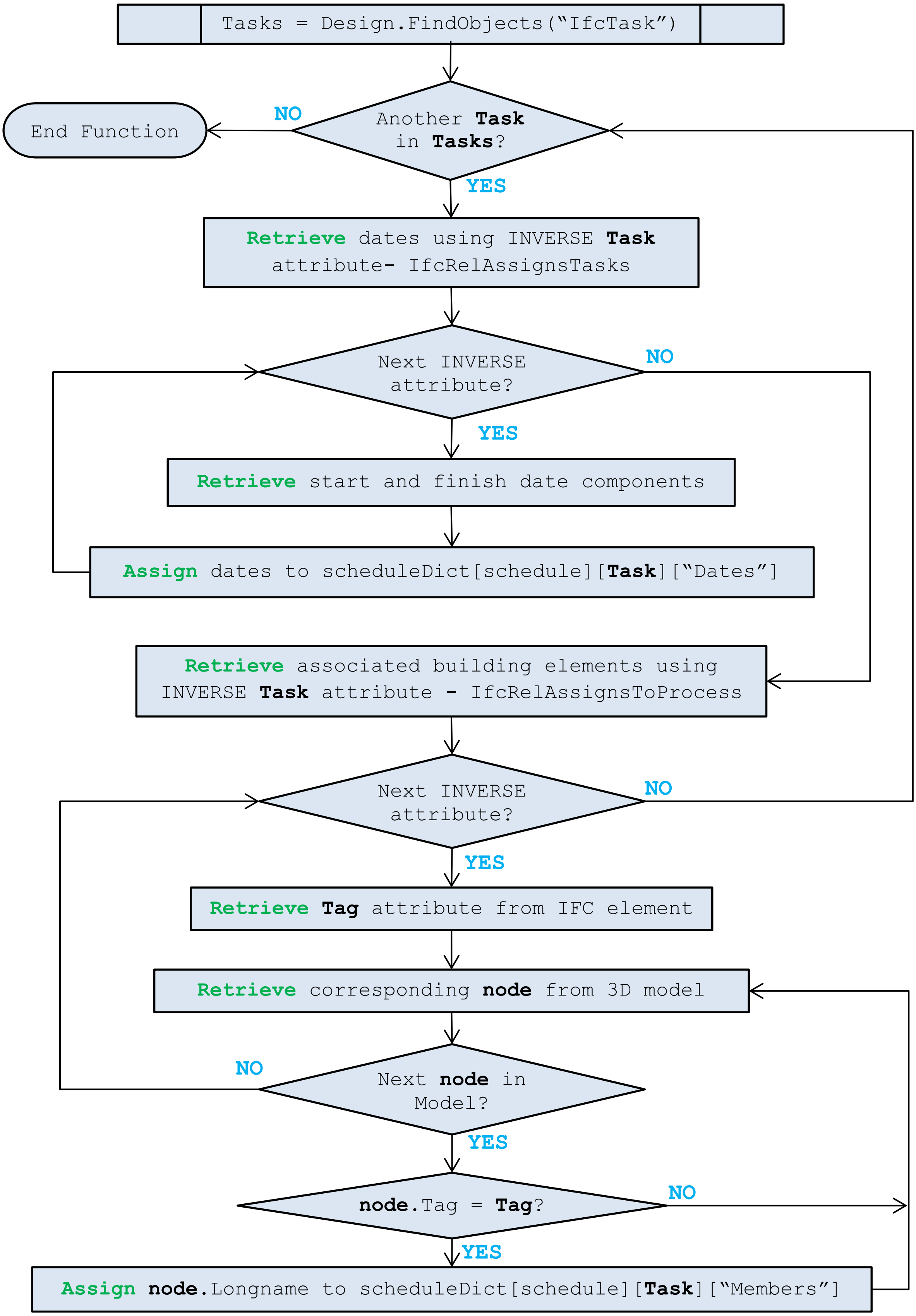


Figure 5-25 The IFC.readScheduleDates() method

`IFC.saveDates` – Enabling a user to store and later retrieve schedule information from the IFC file is a fundamental attribute of the 4DAR project. This IFC class method maps the schedule information in `scheduleDict{}` onto the objectified IFC attributes and relationships that describe a construction schedule. Figure 5-26 illustrates the method by which `scheduleDict{}` elements are conceptually related to IFC object types. Furthermore, it demonstrates how these various IFC types are brought together into a unified construction schedule using the two objectified relationships `IfcRelAssignsTasks` and `IfcRelAssignsToProcess`.

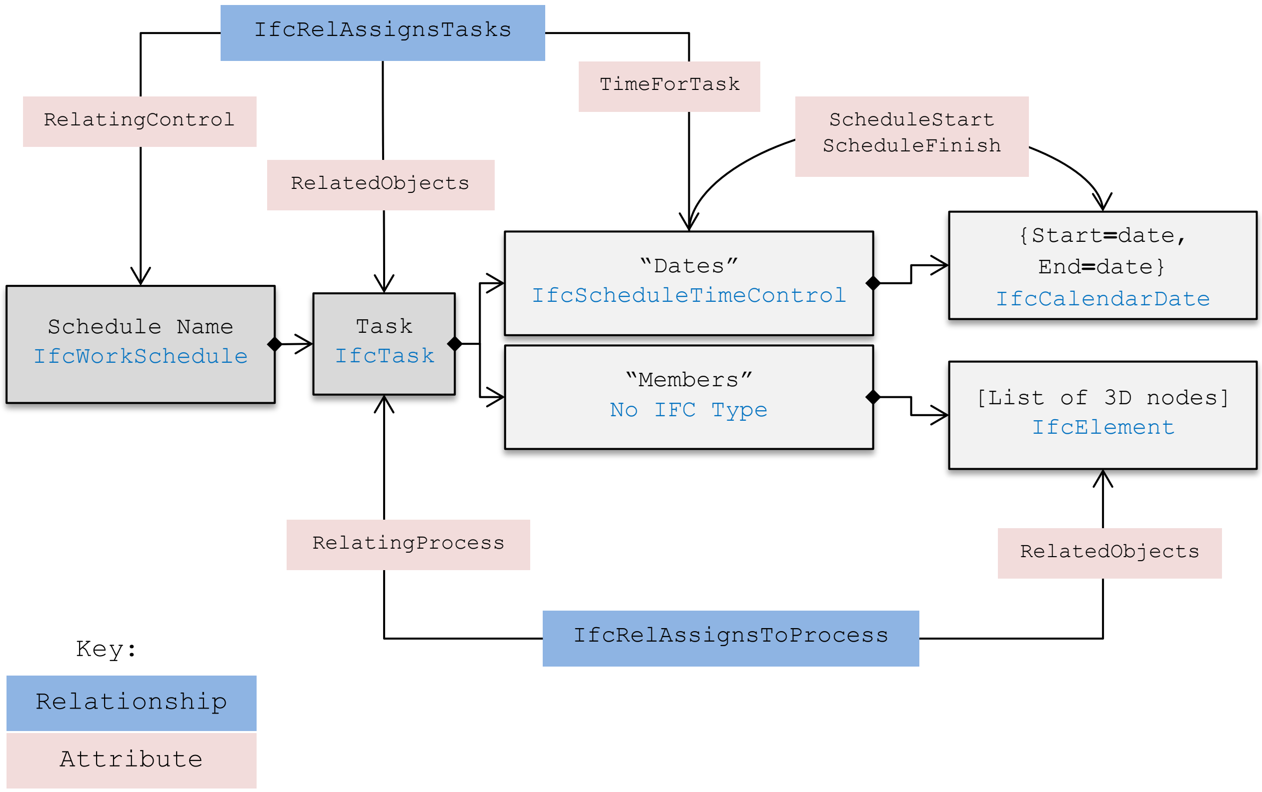


Figure 5-26 Mapping of scheduleDict entities to the corresponding IFC types, relationships and attributes

If no schedule has been loaded from the IFC file then `saveDates()` adds an `IfcWorkschedule` object, names it after the `scheduleName` variable and creates its Global Unique identifier (GUID). However, if a schedule has been loaded from the IFC file, the existing `IfcWorkSchedule` object, held by the `schedObj` variable, is reused by this function. It is worth noting that the GUID is considered to be a non-optional object attribute within the IFC schema and therefore any object added to the IFC file is supplied with a GUID using the method: `IFCsvr.EncodeBase64(IFCsvr.GenGUID)`.

By iterating over each task in `scheduleDict[scheduleName]`, this function creates a corresponding `IfcTask` object and adds it to the IFC design. Each task object added as part of a schedule must also possess a unique `TaskId` number attribute. The class level variable `taskCount` is used to keep track of the number of tasks in the current schedule and therefore can be used to provide each `TaskId`. For every `IfcTask` object that is added to the current schedule, a number of other objects must be created for holding data and describing relationships. The first of these is an `IfcScheduleTimeControl` object; a container which will reference two `IfcCalendarDate` objects which are also created, one for the scheduled start date and one for the scheduled finish.

To assign a task object to the current `IfcWorkSchedule`, a new relationship object is needed, `IfcRelAssignsTasks`. This objectified relationship is created and the task and schedule objects are then allocated to its `RelatedObjects` and `RelatingControl` attributes, respectively. Furthermore, the `IfcScheduleTimeControl` object created for this task is assigned to its `TimeForTask` attribute to relate the defined time constraints back to the current task object. The corresponding date objects are now retrieved from the schedule dictionary, string formatted and assigned to the `DayComponent`, `MonthComponent` and `YearComponent` attributes of the two `IfcCalendarDate` objects. To complete the linking of task and date information, these two calendar objects are defined as the `ScheduleStart` and `ScheduleFinish` attributes of the current `IfcScheduleTimeControl` object.

Finally, a new `IfcRelAssignsToProcess` object is created and associated with the current `IfcTask` object via its `RelatingControl` attribute. The `Members` list at the current `scheduleDict[schedule][task]` entry is then iterated over to retrieve each corresponding `<node3d>`. Using the `<node3d>.p21id` attribute, the corresponding `IfcElement` is retrieved from the underlying IFC data and assigned to the current task using the `IfcRelAssignsToProcess` attribute `RelatedObjects`. This attribute describes a one-to-many relationship, and as such any object that is added in must describe its index, or position in the list. To this end, the class level variable `objCount` is leveraged to keep a tally of the tasks being added to this attribute and is thus employed to define the current objects index when it is added to `RelatedObjects`.

`IFC.saveDesign` – This class method simply calls the `Ifcsvr.Design.Save` function to save the current IFC data that is held in memory by the IFCsvr out into a new physical IFC file that is created when the 4DAR application is terminated.

5.7 THE COMPASS AND GPS MODULES

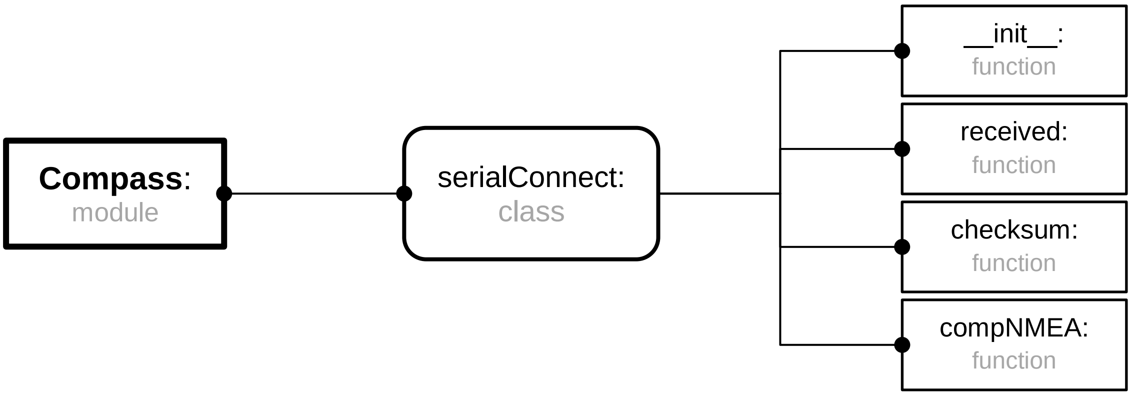


Figure 5-27 The structure of the Compass module

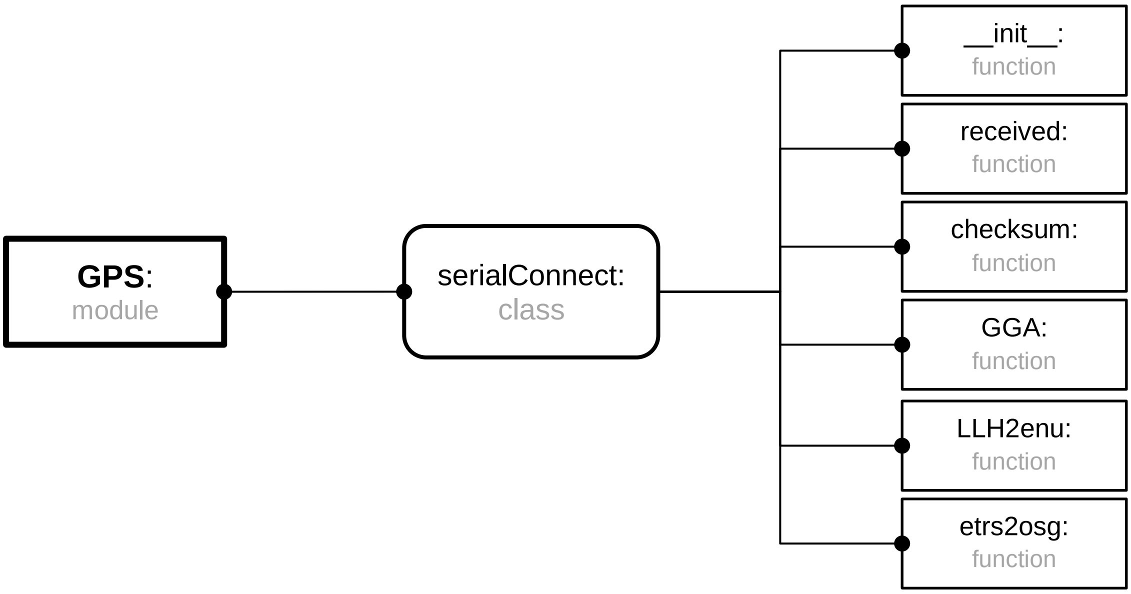


Figure 5-28 The structure of the GPS module

The `Compass.py` and `GPS.py` modules both employ the PySerial module library to connect to the tracking equipment using standard serial port protocol implemented through USB or Bluetooth connectivity. As such, they both employ the same base class functionality for defining a serial connection and retrieving data from the equipment. The **`serialConnect`** class is called with the serial port name and the baud rate of the specific equipment. The `__init__` method, or constructor, then attempts to open the specified port and connect to the equipment before defining the buffer variable which is used by the `received()` method. This buffer is used to collect the packets of data sent over the serial port before the NMEA sentence is parsed out. Both of these modules are instantiated by the View module and are controlled by module level timers that are set at the update rate of the equipment in question.

Once the serial port connection has been successfully established, the `received()` method reads in the compass data in the form of comma delineated NMEA sentences every time it is called by the `View.compTimer()` function. Every NMEA sentence ends with a checksum, a standard 128-bit hash value created by the MD5 cryptographic algorithm that is unique for each collection of data. Using a similar MD5 checksum generator, it is then possible to verify the data by comparing the hash value present in the sentence string with a newly created one. Using this approach, each sentence is checked for missing or corrupted data using the hash checker routine, `checksum()`. If the checksums are identical then the data representing the heading, pitch and roll in degrees is extracted and returned to the calling function as three floating point numbers by the `compNMEA()` method.

Using the same approach as the compass module, the GPS module reads in the GPS data over the serial connection and verifies the data using the `checksum()` method every time its `received()` method is called by `View.gpsTimer()`. The main body of this module is comprised of a set of methods that implement the projection and transformation of the raw GPS coordinates onto the UK national grid easting, northing and height above ellipsoid. The GPS latitude, longitude and altitude readings are parsed from the NMEA sentences with the prefix ‘$GPGGA’ by the `GGA()` method. The latitude and longitude are then converted to eastings and northings by the `LLH2enu()` method using a Transverse Mercator projection, as prescribed by Ordnance Survey (Ordnance Survey, 2012b). Using the most current Ordnance Survey transformation, OSTN02, together with their OSGM02 Geoid model, the `etrs2osg()` class method then transforms the grid references from GPS coordinate system ETRS89 (European Terrestrial Reference System) to the OSGB36 National Grid coordinate system

.

Table 5-1The Ordnance Survey OSTN02 shift table

Record No.	ETRS89 easting (m)	ETRS89 northing (m)	OSTN02 east shift (m)	OSTN02 north shift (m)	OSGM02 Geoid Ht (m)	Geoid datum flag
1	0	0				
2	1 000	0				
3	2 000	0				
...	...	...				
876 949	698 000	1 250 000				
876 950	699 000	1 250 000				
876 951	700 000	1 250 000				

Both the transformation (OSTN02) and the new Geoid model (OSGM02) are implemented through a data table provided by Ordnance Survey in the form of a text file. This data record contains a 700 km east-west by 1,250 km north-south grid of translation vectors recorded at the same 1 km resolution as the national grid. Table 5-1 illustrates how the comma delineated text file is organised with each record occupying a single line, or row, in the file. To transform the ETRS89 value obtained with `LLH2enu()` to OSGB36, bilinear interpolation is used to obtain the exact transformation value from the values at the four corners of the kilometre square in which the point falls. The interpolated values thus obtained are then added to the ETRS89 easting and northing, and to the raw altitude reading to obtain the corresponding OSGB36 coordinate values.

```
******************************************************************************
** Loading GPS_01.py
******************************************************************************
** Load Time: 0.86 seconds
---
$GPGGA,151053.00,5235.3056480,N,00207.6518645,W,4,11,1.17,161.1512,M,48.3596,M,1.0,0001*60
GPGGA,151053.00,5235.3056480,N,00207.6518645,W,4,11,1.17,161.1512,M,48.3596,M,1.0,0001

OSGB easting =  391456.558
OSGB northing =  298965.754
orthometric height =  110.649



---
$GPGGA,151054.00,5235.3056450,N,00207.6518642,W,4,11,1.17,161.1463,M,48.3596,M,1.0,0001*6AGP
GGA,151054.00,5235.3056450,N,00207.6518642,W,4,11,1.17,161.1463,M,48.3596,M,1.0,0001

OSGB easting =  391456.558
OSGB northing =  298965.749
orthometric height =  110.644



---
$GPGGA,151055.00,5235.3056470,N,00207.6518621,W,4,11,1.26,161.1557,M,48.3596,M,1.0,0001*68
GPGGA,151055.00,5235.3056470,N,00207.6518621,W,4,11,1.26,161.1557,M,48.3596,M,1.0,0001

OSGB easting =  391456.56
OSGB northing =  298965.752
orthometric height =  110.653
```

Figure 5-29 GPS module print out

Figure 5-29 shows a debug print out created by the GPS module during development. Each subsection begins with a NMEA 0183 version 3.0 coma delineated sentence which is parsed out of the ASCII data block that is received via a serial port connection from the GPS unit. Several sentence types are available from GPS equipment; each having a different focus or purpose. Indeed, multiple sentences are often output in each cycle of the GPS equipment. The TopCon HiperPro RTK-GPS equipment used during development process provided various NMEA sentence output options; however it was possible to send instruction via the serial connection using the GNSS Receiver Interface Language (GRIL) enabling control over various parameters, including update rate and NMEA sentence type. For example, the python command - `ser.write("%%em,/dev/ser/b,nmea/GGA:1\r")` was executed once the serial port connection had been established and instructed the TopCon GPS unit to commence output of the NMEA sentence GGA via the receiver’s port b at a rate of 1Hz. The GGA sentence contains the minimum GPS fix data required for real time 3D location, including the Universal Coordinated Time (UTC), the position and other fix related data. A full breakdown of the 14 individual message fields within the GGA sentence is as follows:

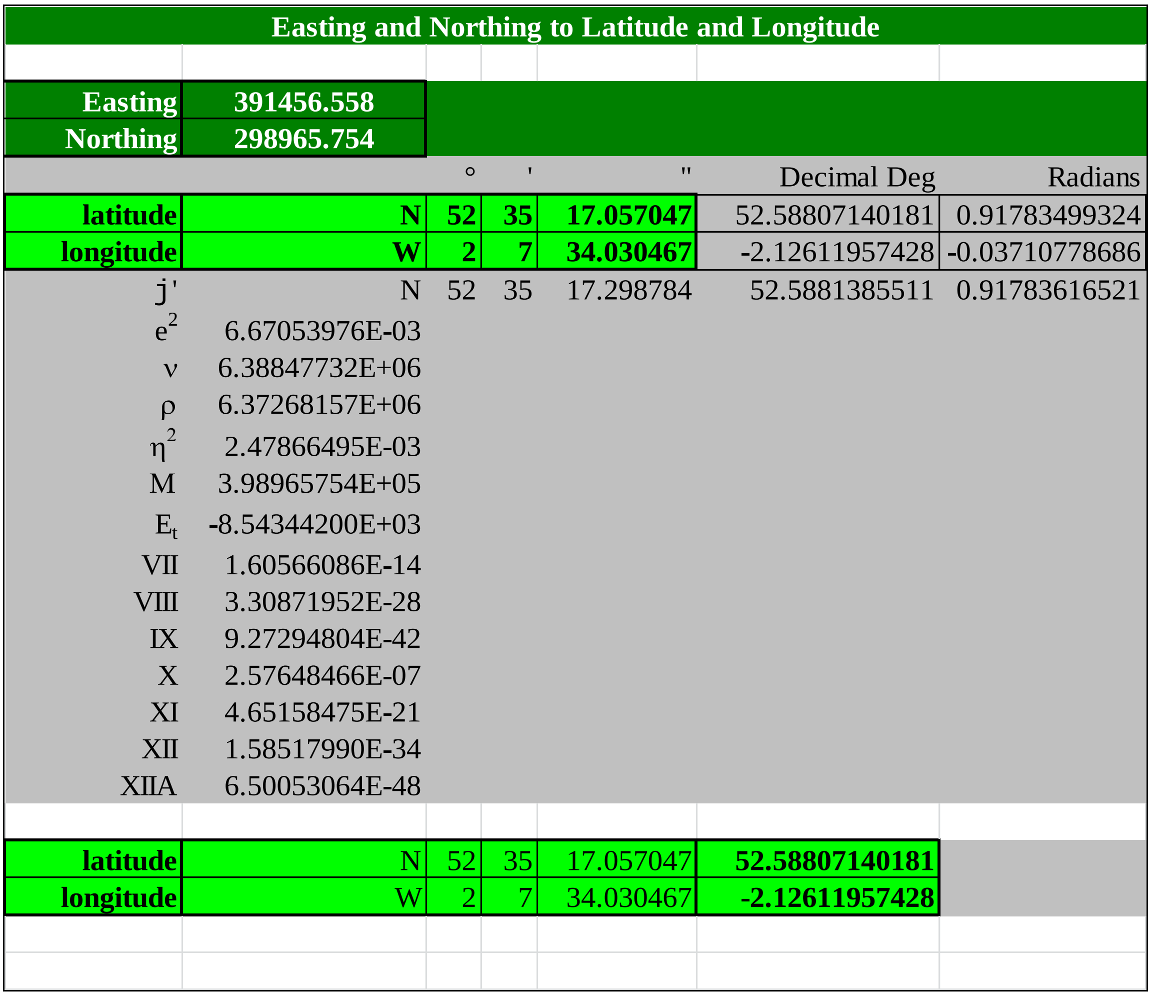
```
$GPGGA,151054.00,5235.3056450,N,00207.6518642,W,4,11,1.17,161.1463,M,48.3596,M,1.0,0001*6AGP

  1   ,   2    ,    3       ,4,      5      ,6,7,8 , 9  ,   10   ,11,  12 ,13, 14, 15   16
```

Field	Description
1	Sentence Identifier
2	UTC of position fix in HHMMSS.SS format
3	Latitude in DD MM.MMMM format
4	Direction of latitude – N: North, S: South
5	Longitude in DDD MM.MMMM format
6	Direction of longitude – E: East, W: West
7	GPS fix quality - 0: fix not valid, 4: Real-time kinematic, fixed integers 1: GPS fix, 5: Real-time kinematic, float integers 2: DGPS fix
8	Number of satellites in use, 00 to 12
9	Horizontal Dilation of Precision(HDOP)
10	Antenna height – Altitude above mean sea level
11	Units of antenna height - “M” indicates metres
12	Height of geoid above WGS84 ellipsoid (Geiodal separation)
13	Units of geoidal separation “M” indicates metres
14	Age of Differential GPS data in seconds
15	Differential reference or Base station ID
16	Checksum, used to check for data integrity or transmission errors

Table 5-2 Breakdown of the GGA NMEA sentence (Trimble (2004))

To verify the accuracy of the northing and easting coordinates produced from the raw GPS latitude and longitude by the GPS module, a spreadsheet application was downloaded from an Ordnance Survey web page. This macro enabled spreadsheet carries out all the common coordinate calculations based upon their prescribed methodology and therefore enables the output of 4DAR's GPS module to be checked (Ordnance Survey, 2012a) (see Table 5-3).

Table 5-3 Snapshot from worksheet in OS spreadsheet showing conversion between ETRS89 latitude and longitude and OSGB36 easting and northing



Easting and Northing to Latitude and Longitude

Easting	**391456.558**					
Northing	**298965.754**					
		°	'	"	Decimal Deg	Radians
latitude	**N**	**52**	**35**	**17.057047**	52.58807140181	0.91783499324
longitude	**W**	**2**	**7**	**34.030467**	-2.12611957428	-0.03710778686
j'	N	52	35	17.298784	52.5881385511	0.91783616521
e^2	6.67053976E-03					
ν	6.38847732E+06					
ρ	6.37268157E+06					
η^2	2.47866495E-03					
M	3.98965754E+05					
E_t	-8.54344200E+03					
VII	1.60566086E-14					
VIII	3.30871952E-28					
IX	9.27294804E-42					
X	2.57648466E-07					
XI	4.65158475E-21					
XII	1.58517990E-34					
XIIA	6.50053064E-48					
latitude	N	52	35	17.057047	**52.58807140181**	
longitude	W	2	7	34.030467	**-2.12611957428**	

Chapter 6

6 User Evaluation Analysis

6.1 INTRODUCTION

Based on the conceptual framework and proposed approach discussed in Chapter 4, Chapter 5 presented the implementation and operational concepts of a tool for 4D model based planning in outdoor AR (4DAR). This tool is envisioned to enable construction planners to dynamically plan, visualise, edit and communicate a construction schedule using outdoor AR, BIM and 4D planning techniques. This chapter presents the results of the user evaluation strategy that was adopted to evaluate the novel proposed approach to construction planning, the success with which the implemented prototype addressed the prominent issues identified within the conceptual framework and the usefulness of such a system in the opinion of the evaluators consulted in this evaluation process.

Section 6.2 presents the results from the first section of the post evaluation questionnaire which seeks to ascertain the level of understanding possessed by each evaluator concerning current and emerging approaches and applications in construction IT. The results presented in Section 6.3 provide the opinions of the evaluators on the application of AR within the construction planning process for contextual data visualisation. Section 6.4 provides a post use evaluation of the usefulness of the interactive 4D CAD planning approach implemented through the developed software prototype. Section 6.5 sets out the results from the final section of the questionnaire which examined the evaluators' opinions towards the utilisation of BIM within the planning phase of a construction project.

6.2 EVALUATOR CHARACTERISTICS

Nine construction professionals and post graduate construction students were approached to undertake evaluation of the implemented prototype software planning tool. These individuals were chosen to provide a variety of experience and levels of expertise within the construction industry and appreciation of current trends and research efforts relating to construction IT and management approaches. A breakdown of the evaluators is given in Table 6-1.

Table 6-1 Details of evaluation participants

Current Position	Industrial Experience
Technical Co-ordinator and Trainee Construction Manager.	Project Management. Producing divisional programmes and site duties whilst working on a construction project (building a Passivhaus school)
BIM Administrator and Project Manager	Creating a BIM document management system - Standardising information which is imported into 3D (BIM) models.
Architect	Resident architect, developing project design briefs. Designing low-scale building projects.
Architect	Developing a range of commercial designs and management of building projects.
Interior Architect	Commercial and industrial refurbishment projects. New build multi-storey private accommodation projects.
Surveyor / Part time post graduate Construction student	Not Given
Full Time post graduate Construction student	Not Given
Full Time post graduate Construction student	Not Given
Full Time post graduate Construction student	Not Given

The principal objective of the user evaluation sessions was to enable industry professionals and post graduate construction students to provide feedback on the potential benefits of the proposed approach to interactive on-site 4D construction planning. Furthermore, these sessions also enabled the evaluators to provide evidence on the level of success with which the implemented prototype planning tool realized the key attributes specified within the conceptual framework.

As per the evaluation protocol set out in Chapter 4 (Section 4.4.1), the evaluation sessions were comprised of three distinct units. Firstly, a presentation was given that defined the aims of the study and an overview of the approach and architecture of the implemented prototype. Following this initial presentation, the evaluators were shown video examples of the implemented tool operating in AR mode, before being guided through a practical session of the prototype system being used in desktop mode. The final stage of the user evaluation comprised a web based, reflective questionnaire to enable the collection of the feedback. Throughout these evaluation sessions, ad-hoc discussions took place, during which the evaluators provided additional informal feedback and comments regarding the applicability and usefulness of the proposed approach and implemented prototype tool.

The questions within the initial section of the questionnaire were designed to determine the level of understanding of each respondent regarding current and emerging construction IT applications and approaches. This information determined the extent of knowledge of the respondents with current 3D and 4D CAD tools. The results obtained showed that while 100% of the respondents had at least some experience of 3D CAD tools, 78% of the evaluators had no experience with current commercial 4D CAD applications. Following on, only 11% of the evaluators stated that they had no knowledge of either Building Information Modelling or IFC files, while 55% were at least somewhat familiar with the concept of Augmented Reality (AR) prior to the evaluation session. These results assisted in evaluating the ease of use and usefulness of approach of the implemented prototype, through assessment of the individuals' familiarity with the underlying technology employed in this study. The fundamental principle of the implemented 4D tool does not draw on current commercial 4D CAD techniques; therefore these results negate the potential of user bias based upon prior experience in this area.

6.3 AR IN CONSTRUCTION

The second section of the questionnaire sought to obtain the opinion of the evaluators on the application of augmented reality for contextual data visualisation within the construction planning process. Based upon the generic attributes in the idealised framework, the usefulness of approach taken in the implemented prototype was tested, together with the potential of an outdoor AR system to enhance the contextual and spatial understanding of a 3D building design.

6.3.1 General Technology Attributes

Based on attributes in the technology domain of the proposed framework, the usefulness and potential benefits of outdoor AR for construction planning were tested. Specifically, the attributes relating to enhanced perception and contextual visualisation within an augmented workspace were examined using the evaluation protocol developed in Chapter 4. The results from this phase of questioning are illustrated in Table 6-2.

Table 6-2 Results for the technology attributes for AR in construction scheduling

Question	**Strongly Disagree**	**Disagree**	**Agree**	**Strongly Agree**
Full scale "in-place" visualisation with by outdoor AR has potential to enhance planning operations			5 *56%*	4 *44%*
On-site construction planning would enhance planning operation			4 *44%*	5 *56%*
Visualising 4D construction simulation in outdoor AR would enhance understanding of a construction schedule		1 *11%*	2 *22%*	6 *67%*

These results establish the potential benefits of leveraging untethered, on-site AR technology. 100% of respondents agreed that outdoor AR would enhance planning operations. It was noted that by providing a full size visualisation of the design intent within the context in which it is to be built would enhance understanding of the spatial context of the buildings' design. Furthermore, all the evaluators felt taking planning operations onto the construction site would be beneficial to the planning process. 89% the evaluators also answered that deploying 4D CAD simulations using outdoor AR technology would improve understanding of a proposed construction sequence. Furthermore, many of the reviewers commented that they saw untethered hands-free outdoor AR being particularly well suited for general data delivery and visualisation on a construction site.

6.3.2 Future Potential

The evaluators were next asked to comment on future potential and trends within the construction industry for the application of outdoor AR. 100% agreed that there was much potential for enhancing and improving on site operations using this technology. Next, they were provided with a list of 3 potential areas in which outdoor AR could provide enhancement; they were not limited to one choice here. Interestingly all respondents felt that construction scheduling stood to benefit the most from application of this technology, while 67% felt work space planning and 56% felt that safety planning could be enhanced through the application of an untethered outdoor AR approach to visualising spatial data.

6.4 INTERACTIVE 4D CAD

The focus in the third section of the questionnaire was to evaluate the usefulness of the interactive 4D CAD approach for plan creation. This functionality within the implemented prototype enables a schedule of construction tasks to be created through direct interaction with a 3D building model.

6.4.1 General Technology Attributes

The developed functionality employed during the interactive 4D planning sessions, sought to exhibit the generic attributes for Interactive 4D planning proposed in the conceptual framework. The ease of use for the implemented 4D planning approach was tested. The evaluators were questioned regarding the ease with which the component tasks of the 4D planning approach could be undertaken using the implemented graphical user interface, testing the efficiency of the interface design. The process and concept of using 3D building model elements as an interface for interactively creating construction tasks was next examined. Iterating between planning and reviewing are key to the planning approach implemented by the 4DAR prototype; this approach was evaluated based upon the ability to view construction simulations throughout the planning process.

Table 6-3 General technology attributes for interactive 4D planning

Question	**Strongly Disagree**	**Disagree**	**Agree**	**Strongly Agree**
It was simple to interact with the 3D model to create the sequence of tasks.		1 *11%*	6 *67%*	2 *22%*
The prototype application interface and menu were easy to understand		3 *33%*	4 *44%*	2 *22%*
The process of assigning dates to selected objects as tasks was easy to understand		1 *11%*	5 *56%*	3 *33%*
It was useful to be able to visualise the construction sequence throughout the planning process			5 *56%*	4 *44%*

The results demonstrate that the overall planning approach implemented within the 4DAR prototype was found to be effective by the evaluators. 89% of respondents felt that it was easy and understandable to use an interactive 3D model as an interface for creating a sequence of construction tasks. Several evaluators commented that this approach made more sense, especially as buildings are predominantly designed in 3D. Moreover, one respondent noted that plans and elevations take skill and experience to fully understand, whereas a 3D model is more readily understood even by inexperienced personnel.

The prototype interface and menu system proved to be a more divisive subject. 33% of evaluators felt that it was not easy to understand, and while 22% felt it very easy to navigate and use the interface devices, some of the remaining 44% that agreed it was easy to use expressed some caveats. The main shortfalls in the interface design were stated as being the use of drop down menus. These were implemented as partially transparent panels with opaque text entries listed within. It was felt by several evaluators that this design feature caused the menu entries to be somewhat difficult to read; something that it was felt would be compounded when being used in outdoor AR mode.

A central feature of the planning method developed for this study is the concept of applying 4D CAD to the creation of a schedule of construction tasks, rather than as a tool for post planning review. 89% of evaluators felt that the concept and the process of creating construction tasks by assigning date ranges to 3D building model elements was easily and readily understandable. It was felt by most that this direct mapping between a construction task and its component building elements seemed logical. Nevertheless, one respondent stated that in a large building project, this approach may become confusing and would possibly benefit from an on-screen diagrammatical representation of the scheduled tasks for navigation of the schedule in real time.

Visualising the construction sequence throughout the planning process is a key feature of the iterative planning approach developed in this study. This feature is central to the unified workflow of scheduling, reviewing, editing and confirming a construction sequence in a single application adopted in this study. All of the evaluators felt that this was a very useful feature of the implemented prototype, with 78% giving the highest agreement score. One evaluator noted that this ‘visualise whilst planning’ approach would be especially valuable for inexperienced or student construction planners.

6.4.2 Future Potential

The final question in this section saw the evaluators asked to comment on the viability and potential of an interactive 4D CAD approach to construction planning. All of the evaluators stated that, in their opinion, this approach provided a potential future alternative to the traditional construction planning paradigm. Several respondents commented using a visual approach to the planning process would enhance understanding and communication of the schedule intent and enable planners to better understand the implications of their decisions. One evaluator stated that this approach to construction planning could be used to bridge the planning skills gap within the construction industry. Others highlighted that an interactive 4D planning tool would be a valuable educational tool, enabling trainee planners to easily visualise the outcomes of different planning strategies. Nevertheless, it was also noted that despite the potential benefits afforded by an interactive 4D planning tool, the construction industry is reluctant to adopt new technologies and approaches to working.

6.5 BIM / IFC IN CONSTRUCTION SCHEDULING

The final section of the questionnaire examined the evaluators’ opinions towards the use of BIM within the planning phase of a construction project. More specifically, it sought to test the usefulness of the functional processes facilitated through the use of IFC data within the implemented prototype.

6.5.1 General Technology Attributes

Employing IFC files within the 4DAR prototype enabled BIM data and processes to be leveraged and the general attributes within the conceptual framework to be tested. The objectified and relation-based building information within an IFC file enabled 3D building model elements to be associated with intelligent data regarding their object type and their relationship to the spatial context of the building. The benefit this data provided the planner was tested through the inclusion of intelligent grouping and selection mechanisms in the implemented prototype. Furthermore, by utilising IFC files as a central repository for the schedule information, this approaches' ability to improve communication and interoperability within a construction project was tested. This ability facilitates visualising, editing and downstream communication of schedule information using functionality within the IFC class of the Model module in the implemented prototype. The results from the evaluation of these attributes are highlighted in Table 6-4.

Table 6-4 General Technology attributes for BIM centric construction scheduling

Question	**Strongly Disagree**	**Disagree**	**Agree**	**Strongly Agree**
It was convenient to access building elements via their IFC type or corresponding building storey?			5 *56%*	4 *44%*
IFC files are a viable container for the capture of scheduling data?			6 *67%*	3 *33%*
It is useful to be able to load, visualise and edit schedule data from an IFC file?		1 *11%*	1 *11%*	7 *78%*
There is benefit from utilising IFC files for storing and downstream communication of schedule data			5 *56%*	4 *44%*
BIM provides a useful approach to documentation for construction planning?			3 *33%*	6 *67%*

Categorising the building elements within the 3D model by their IFC type and the building storey on which they resided facilitated the provision of intelligent selection mechanisms within the implemented prototype planning tool. 100% of respondents felt that this was a very useful feature, facilitating quick and convenient methods of selecting groups of elements within the building model. It was noted by many of the evaluators that, without this mechanism, the process of selecting individual building elements before defining a date range would be a laborious and time consuming task.

BIM provides a process and mechanism for centralising all data relating to the complete lifecycle of a building. Moreover, the IFC file format makes provision for this process by the inclusion of structures within its schema for capturing this widely variant and voluminous amount of data. A central feature of the 4DAR approach to construction planning is the use of IFC files to capture, store and therefore enable communication of the schedule information created within its interactive 4D planning approach. When questioned, 100% of the evaluators felt that this was a practical method for capturing and storing schedule information despite the fact that this aspect of the IFC schema was not currently exploited or supported by any planning software packages.

Providing a mechanism for capturing a construction schedule within the IFC file provides a potential solution to the fragmented documentation approach in traditional construction planning techniques. Nevertheless, in isolation, this feature does little to enhance communication of the schedule intent. The ability to load schedule data from an IFC file into the prototype system, visualise the inferred construction sequence provides a robust method of schedule communication. Furthermore, the implemented prototype enables the user to edit the loaded sequence of tasks and re-save if required, fostering collaborative working practices within the scheduling framework. 89% of the evaluators agreed that it was useful to be able to interact with schedule-related data in an IFC file in a way that mirrored the functionality provided for user created schedule data. Although, one respondent felt that the ability to export the schedule data to industry standard formats, such as Microsoft Project or Autodesk Navisworks, was missing from the prototype tool. Furthermore, 100% of the respondents agreed that utilising IFC files as a central repository of all the schedule information would provide benefits for storage and downstream communication of the schedule throughout the planning team and construction team as a whole.

6.5.2 Future Potential

The final question in the evaluation exercise asked the evaluators to comment on the use of BIM within the planning phase of a construction project. Specifically, their opinions were sought regarding its use as an approach to construction scheduling documentation. All of the respondents felt that there was much benefit to be had from utilising the BIM as a central repository for all construction data, including the construction schedule. It was noted that current planning software does not subscribe to this centralised solution to construction data, i.e. they do not support the IFC file format in regards to scheduling data. One respondent noted that BIM's centralised approach to building data could negate the need for the excessive amounts of paperwork associated with planning and construction in general. While many of the evaluators felt that the BIM centric approach to construction planning advocated in this study promoted a traceable, intelligent and centralised approach to construction planning informatics. Furthermore, it was felt that it would enhance collaborative planning practices and improved interoperability through its support of the open standards IFC file format.

6.6 SUMMARY

This chapter has presented the results of the user evaluation strategy that was implemented to test the general ability of the 4DAR prototype planning tool and the interactive 4D planning approach implemented within it. The user evaluation was undertaken based upon the protocol defined in Chapter 4. Nine construction professionals and post graduate construction students with a range of experience and knowledge around construction planning and construction IT were used to evaluate the system and the proposed approach. Each evaluation session comprised three discrete segments; an initial presentation of the background to and aims of this study. This was followed by a demonstration and hands-on tutorial session and finally a reflective questionnaire was made available via a shared Google document.

The positive results obtained through the user evaluation demonstrated both the feasibility of the proposed approach to construction scheduling and the success with which the implemented prototype realised the aims specified by the idealised framework in Chapter 4. An objective review of the implemented software tool was obtained through targeted questions within the questionnaire. In addition, the informal feedback obtained from the evaluators throughout the evaluation sessions provided anecdotal evidence of the potential benefits, shortcomings and future applications of the implemented tool not originally envisaged within the study. Finally, based upon known limitations, the future potentials of the proposed approach and implemented tool were presented. Based on user evaluation data provided, an industry based user centric perspective of the potential benefits of the proposed approach to construction planning based around a system of this nature was obtained.

The following chapter presents the overall conclusions of this study. These findings provide an evaluation of the study and discuss the final outcomes in relation to the stated aims and objectives. Finally, suggestions for further work in this area are discussed.

Chapter 7

7 Conclusions and Further Recommendations

7.1 INTRODUCTION

In this final chapter, the entirety of this research is summarised and presented. The chapter begins by presenting a complete review of the thesis and the work undertaken. Following this, the aims and objectives are presented to review the success of the work in achieving these. The contributions to knowledge made by this study are then discussed in detail followed by the review of potential future research work and the impact that the approach developed in this study could make to industry practice.

7.2 REVIEW

Section 1.3 (Chapter 1) set out the overall aims of this study, that is the development of a novel approach and prototype software tool to assist construction planners through the application of object oriented building models, real time simulations and advanced visualisation techniques.

From an extensive review of existing literature in the field of construction planning, it was discovered that, despite the increased prevalence of computer based tools and the increasing utilisation of BIM, it is the experiential knowledge of the planner that underpins most scheduling operations. One computer-based approach that has the potential to improve and enhance construction planning is 4D simulations. Current 4D approaches require a construction schedule to be developed *a prior* and linked to a 3D building model to produce the 4D model. This linking of the temporal and spatial contexts of a building project is a time consuming process that produces visual simulations for post planning review only.

Much research has revealed the potential of Augmented Reality for enhancing understanding and communication of the spatial context and design intent of a construction project. Presenting a digital building design at full scale within the visual context of the real world democratises the design information, negating the need to mentally extrapolate the information from the design documentation. Examples of AR applications provide robust tracking and image registration in controlled or prepared environments. Furthermore, there exist very few applications of AR in construction planning. Utilising GPS for positioning and attitude sensors that directly measure naturally occurring phenomena, the planning process can extend out of the office and onto the proposed construction site.

The literature revealed that current approaches to documentation during the planning and construction phase could result in the planning team being overburdened with information. Further, software interoperability issues constrain data sharing and hinder communication. A review of the existing literature in the field of construction ICT and data management revealed BIM as the prevailing approach to centralise and manage a buildings' information throughout its lifecycle. To facilitate an open and collaborative BIM workflow, and in line with current UK governmental policy (and international initiatives), the open standard IFC data file emerges as the most promising approach. This file format is supported by most construction design tools; however its ability to store planning and schedule data remains unused in current commercial planning applications.

A 4-tier research methodology was adopted in this study. From the findings of the literature review, a conceptual framework was recommended, in which the salient requirements for an interactive, on-site, model based 4D planning system were highlighted. Based upon the developed framework, a proposed approach was presented bringing together the assorted processes required for the development of a novel software planning tool. Following the proposed approach, a prototype software system was implemented. A user evaluation strategy was next developed to enable the implemented prototype to be appraised. The proposed evaluation strategy enabled the implemented prototype to be tested against the attributes and requirements highlighted in the conceptual framework.

Based on the conceptual framework and proposed approach, a prototype software tool was developed for on-site BIM enabled 4D planning, 4DAR. The software prototype was implemented using both commercial and freely available tools, to produce a completely new bespoke software solution. Based upon the Model-View-Controller software design pattern, the implemented prototype satisfied the processes specified in the proposed approach. The implemented tool provided iterative real-time model-based construction planning based around a single, unified user interface. Without the need for previously constructed schedule documentation, this tool enables planners to generate construction schedules directly by interaction with the 3D building model. Using untethered outdoor AR, contextual 4D construction simulations are available for the planner to view throughout the planning process. The implemented prototype also utilises IFC files natively as a central repository for reading and writing building and schedule data. This enables information relating to individual building elements to be mapped automatically against corresponding 3D elements, providing a direct asynchronous link between the geometry and the data model, facilitating the implementation of intelligent group selection mechanisms. Furthermore, schedule data can be written to the IFC file for storage, or loaded from it for 4D visualisation, alteration, confirmation and collaboration.

A user evaluation approach was employed as the primary method of testing the effectiveness and value of the implemented system. This enabled the usability of the implemented software system to be determined, whilst highlighting any limitations of the novel approach to construction planning proposed in this study. Professional practitioners and post-graduate students of construction with professional experience were guided through a three-stage evaluation procedure.

The user evaluation verified that the implemented prototype fulfilled the attributes and requirements of the conceptual framework. In addition, the evaluation highlighted that the respondents felt the prototype tool, and the novel planning approach that it implemented, had the potential to improve and extend current planning methods by leveraging a BIM-enabled approach to construction informatics.

7.3 RESEARCH ASSESSMENT

Within this section, the various objectives stated in Chapter 1 are reviewed against the work completed. The review of each of these objectives allows the assessment of whether the aim has been achieved. Six objectives were specified to facilitate the overall aim of developing a novel computer based approach to BIM-enabled 4D construction scheduling.

Objective	**Evaluation**
Objective 1: To review the scope of research in the area of construction planning, with particular interest in 4D CAD and emerging techniques such as model based scheduling and Building Information Modelling.	To satisfy the criteria set out in the first objective, a comprehensive review was carried out to examine current and emerging industrial practices and research approaches surrounding construction planning, 4D CAD and Building Information Modelling. Documentation overload and misinterpretation negatively impact planning efforts. 4D CAD provides unambiguous representation of the schedule intent. Currently, 4D CAD provides only post planning review, despite research extolling it as a powerful planning tool. BIM provides a streamlined approach to construction informatics throughout a buildings' lifecycle. IFC is an open standards BIM data file that supports data and software interoperability. Despite the inherent ability to capture schedule data within the IFC schema, no commercial tool currently supports this functionality.
Objective 2: To examine current techniques for implementing Augmented Reality within an outdoor environment, to identify and build upon aspects of good practice.	Following, an examination of the current research efforts and state of the art of Augmented Reality (AR) was undertaken to satisfy objective number two. AR is a powerful medium for contextual visualisation and data presentation with much future potential. Most examples in construction research are implemented within a controlled indoor environment. GPS emerged as the first

	choice solution for ad-hoc outdoor position tracking. Real Time Kinematic (RTK) GPS greatly improves the level of accuracy and real time positioning capability; however the line of sight dependency remains. Magnetometers, inertial sensors and gyroscopes measure naturally occurring phenomena and provide an untethered solution for head tracking (rotation). Nevertheless, each solution presents its own set of strengths and weaknesses and therefore the best results will be obtained by combining multiple sensors in a so-called sensor fusion approach.
Objective 3: To design and develop a research-informed conceptual framework to assist in the identification of the important issues surrounding software development within an AR scheduling context.	From the results of the review, a conceptual framework was developed to satisfy the third objective. This framework identified the salient issues and attributes for the development of an outdoor model-based 4D planning software tool. Reduced documentation, streamlined data management, improved interoperability and access to intelligent building information data is facilitated through IFC implementation. 4D CAD techniques are leveraged as an intuitive interactive planning tool. This self-contained approach negates the need for conventional construction planning activities and enhances communication and understanding through information democratisation and unequivocal visualisation. Further enhancements to communication, data perception and visualisation are provided through contextual outdoor AR.
Objective 4: To propose a novel on-site approach to construction planning and the development of contextual 4D simulations within an outdoor AR environment.	The framework developed was used as a base for the development of a proposed approach, which fulfilled the fourth objective. It was proposed that an on-site model-based 4D software planning tool should leverage the enhanced spatially referenced visualisation of outdoor AR. The rich objectified

	and relational data from an IFC file supported an intuitive real time environment for schedule creation through direct interaction with a 3D building model whilst simultaneously providing contextual on-site 4D visualisation. This approach does not require the input of a schedule and therefore also avoids many of the shortcomings associated with traditional construction scheduling operations.
Objective 5: To develop a construction planning tool that provides intuitive interaction with an object oriented building model within AR	Guided by the proposed approach, a novel software tool was implemented, thus satisfying the penultimate objective of this study. Employing robust software design principles, the implemented tool mapped the 3D model with IFC data to facilitate intelligent iterative model based on-site planning. The schedule data is created solely through interaction with the 3D model and captured to the IFC for storage. The system supports loading schedule data from an IFC file, enhancing communication and collaboration efforts within the construction project planning process. An untethered AR approach enables position tracking and image registration within an unprepared environment. This facilitates contextual, iterative on-site planning and 4D visualisation towards the creation of a robust construction schedule.
Objective 6: To determine the effectiveness of such a tool and evaluate its usefulness through evaluation on a real construction project.	Finally, the effectiveness of the implemented tool was evaluated by construction professionals and post graduate construction students to satisfy the sixth and final objective. The implemented review process framed the study within the context of current research and provided the evaluators with first-hand experience of the proposed planning approach and implemented software tool. The results showed that the paperless planning

	approach proposed in this study was seen as having the potential for greatly streamlining the planning process. Planning through interaction with a subset of BIM data via 3D model elements was deemed to be useful and intuitive. Nevertheless, it was noted that such a radically different approach to planning may provide challenges for integration within the construction industry. Finally, it was agreed that AR was a potentially important future technology for the project planning process, although most evaluators felt that robust and easy to operate hardware and software solutions were key to its uptake in this regard.

Table 7-1 Evaluation of the objectives specified for this study

Based on the above analysis, the specified aims and objectives have been fulfilled by the work outlined in this thesis and the implemented software tool.

7.4 CONTRIBUTION TO KNOWLEDGE

Throughout the work undertaken for this study, several contributions to knowledge have been made in the areas of 4D CAD, AR in construction and Building Information Modelling. The following sections present the salient contributions to knowledge made by this study.

7.4.1 Integration of Outdoor AR and 4D Construction Planning

This study advocates the use of 4D CAD techniques for schedule creation through real time interaction with a construction product model. The approach adopted for this study further extends the scope of 4D CAD out of the office by leveraging AR technologies. By employing position tracking technologies that require no preinstalled infrastructure, this approach facilitates ad-hoc outdoor 4D planning and visual construction simulation that could be deployed in context on a proposed construction site.

7.4.2 Development of a novel approach to planning in augmented 4D through decomposition

The novel 4D AR approach to construction planning proposed in this study combines the planning and visualisation phases into one iterative and unified activity; facilitating the creation of construction tasks through the decomposition of the construction product model within an AR environment. Construction tasks are created simply by selecting objects within the 3D model and assigning date ranges for their construction. Implied construction sequences thus created can be visualised as a 4D simulation for verification throughout the planning process, allowing the planner to verify and amend any sequence errors on-the-fly. This inherently flexible approach provides adaptive 4D CAD visualisations that reflect changes made to the planning sequence in real time.

7.4.3 Integration of BIM / IFC data with a real time AR environment

The methodology developed in this study provides a novel approach to leveraging intelligent building information data through a real time augmented reality interface. By automatically extracting and mapping a specific subset of BIM data with 3D model elements, this approach facilitates the integration, utilisation, interrogation and interaction with building information data in a real time augmented reality environment. Furthermore, the mapping of 3D elements to IFC objects during initialisation also facilitates asynchronous communication and data flow between the implemented application and the IFC file.

7.4.4 An original approach for leveraging IFC files for capturing schedule data within a real time 4D planning and visualisation environment

The approach developed in this study implements an asynchronous communication mechanism between the real time environment and the IFC data file. This mechanism enables construction schedule data created by the user during the 4D planning session to be written back to the IFC file. To enable communication and collaboration throughout the planning process, the developed software tool can also load schedule data from an IFC file into its own internal data structures for visualisation, verification or revision. This is facilitated by internally organising schedule information data in a manner that is analogous to the objects and relationships relating to planning information within the IFC schema. This novel approach leverages the IFC files for capturing, sharing and utilising schedule information in the context of 4D construction planning and visual simulation.

7.5 RECOMMENDATIONS FOR FURTHER STUDY

This study presents a prototype system implementing a novel on-site 4D construction planning approach which could improve the planning process, thus potentially avoiding costly task sequencing errors during the construction phase. Nevertheless, during the course of this study, additional issues and features have been identified which could further improve and enhance the process of 4D planning and visualisation during the construction planning process. The following recommendations are divided into two discrete areas. The first discusses potential extensions to the underlying research that supported the development of the novel planning approach developed in this study. The second category presents potential technical enhancements to future developments of the implemented software tool.

7.5.1 Research extensions

The IFC data file is emerging as an important UK government backed technology for harnessing the power of BIM throughout the whole construction industry. However, issues surrounding the wider implementation of the BIM standard remain; especially in the planning process with its continued reliance on a fragmented paper trail of documentation and proprietary computer files. This is further compounded by the lack of software support for planning related IFC data in current project planning and 4D CAD tools. To this end, this study has sought to advance the application of this non-proprietary building information file into the area of construction planning and 4D visualisation. It has shown that IFC can already be a viable approach for construction planning data management and 4D CAD simulations. Future research efforts should seek to build consensus for the application of BIM / IFC functionality for 4D simulations. Additionally, formalising a generalised framework for the application of IFC files within construction planning informatics would further the implementation of BIM throughout the construction process and the industry as a whole.

The approach adopted in this study sought to leverage the experiential knowledge of a construction planner within a contextual visual planning environment. The work presented provided the planner with the ability to simultaneously plan and visualise a construction sequence within the same application. Future work could provide a semi-automated approach to construction planning to further support the planner, based on an inherent heuristic knowledge of construction practices. Guided by the additional input of the construction planner, this system would learn over successive projects to apply current best practice to the sequencing of construction tasks. It is envisaged that such an approach would never fully automate the planning process, as the professional experience of the construction planner would be required for any new or novel construction approaches and problems.

Workspace requirements and health and safety considerations could have significant implications for robust and effective planning of a construction sequence. This is an area not investigated in this particular study. Future research initiatives will integrate real time construction sequencing with workspace considerations to provide a more robust and unified approach to 4D planning and visualisation. Utilising technologies such as a managed library of space requirements, or heuristic knowledge based around a dynamically managed database, the planner could incorporate workspace considerations into the construction planning process. Furthermore, this extended unified approach to 4D construction planning and visualisation could incorporate health and safety considerations that are linked to the sequencing of trades and the spatial requirements for the tasks being undertaken.

Addressing the reported skills gap emerging within the construction planning profession is an important challenge facing the construction industry. By providing real time visual feedback of the construction schedule under development, this approach could prove invaluable for trainee construction planners. However, researching this approach to the training of construction planning is beyond the scope of this study. Future investigations could examine the use of the unified 4DAR approach to construction planning and visualisation as an innovative educational tool. Building on the constructivist approach to learning, it is envisaged that future construction planning students could benefit from a learning-by-doing paradigm that could be provided by such an approach.

7.5.2 Software enhancement

The software tool developed for this study implemented Real Time Kinematic GPS to provide untethered location tracking in an unprepared outdoor environment. GPS is an ever improving solution for accurate outdoor location and positioning. The European satellite positioning system, Galileo, will be interoperable with existing GPS and GLONASS technologies, further enhancing the accuracy and coverage capability of these ad-hoc positioning solutions. However, the effective deployment of a satellite based navigation system will always be dependent upon certain environmental factors, such as occlusion of sky in built up urban areas. This has implications for its implementation for positioning and registration within an AR based construction planning application. Future enhancements will need to investigate methods of mitigating these shortcomings through the implementation of complementary technologies. Examples of these may be ground-based mapping and positioning networks, or computer vision techniques based on an inherent or learnt knowledge of the surrounding environment built up using a Simultaneous Localisation And Mapping (SLAM) technique.

Attitude or gaze tracking is vital to ensure that the system knows in which direction the user is looking. In combination with the position tracking solution it is vital for registration within the augmented environment. A tilt compensated digital compass was used in this study for tracking the rotational movement of the users head. This provided a solution for ad-hoc head tracking that required no preparation of the environment. However an issue with this approach was the amount of latency it introduced into the tracking system producing noticeable lag in use. Another issue was the amount of noise in the sensors signal, leading to jittery or jumping movement of the digital artefacts within the augmented view of the real world. Sensor fusion is an approach that seeks to offset the shortcomings of one technology with the strengths of another. Tilt compensated compasses already combine accelerometers with magnetometers to provide a more responsive and robust solution than a compass alone. Nevertheless, future versions of this system should adopt an extended sensor fusion approach to include gyroscopic sensors and software based tracking approaches based on computer vision techniques.

Geometrical form is only one part of the complete BIM dataset relating to a building design and is purely an implied attribute within an IFC file. The approach adopted by this study leveraged the export capabilities of Autodesk Revit to produce an IFC and an FBX 3D geometry file from a single Building Information Model. The FBX model file was then further processed through 3DS Max into an OpenSceneGraph (OSG) geometry file for inclusion in the real time environment. This process was found to prove problematic for some complex structural components such as stairs and curtain walls. Such objects are organised within the IFC file in aggregate under a parent node that holds the IFC name and Tag number for that component, or group of components. For example, the `IfcStair` object contains no direct reference to geometric data itself; it instead acts as parent under which geometrical objects pertaining to the stairs structure are aggregated. During the process of converting the Building Information file to an OSG file, only nodes containing actual geometry are converted, leaving the stairs as a collection of individual geometry nodes referenced only by their IFC GUID number or material properties. This in turn required 3D model re-engineering work to take place within 3DS Max to replace the disparate geometry nodes under a new parent node named according to the original IFC name and Tag. Future developments of this tool will utilise the FBX file directly, or explore direct geometry extraction from the original IFC, thus preserving the integrity of the model hierarchy and negating the need to re-engineer the 3D model.

The implemented software prototype utilises a novel approach to construction planning focused around real time interaction with an augmented 3D building model. This produces a constantly evolving 4D visual simulation model as the sole method of visualising the construction schedule. Future approaches could extend this approach by providing an additional feature where the construction sequence being developed could also be viewed in a more conventional diagrammatical format. The schedule data generated within the 4D planning environment could be mapped against a more conventional presentation format, such as a Gantt chart or spread sheet. Presenting the data in a format that is familiar to current construction planners and fits with current industry practice and would thus encourage the uptake of this novel approach to schedule creation.

Using an approach to planning based around the decomposition of a 3D product model, the implemented tool in this study facilitates a purely linear planning approach, whereby building elements are grouped into tasks and sequenced by assigning date ranges to them. While it proved understandable and intuitive in use, this approach does not provide the ability to specify dependencies between the defined construction tasks. Further extensions to the software tool should incorporate the ability to specify predecessor and successor tasks within the construction schedule which could then be added to the `IfcWorkSchedule`. These dependencies or sequencing constraints are described within the IFC schema by the logical relationship descriptor `IfcRelSequence.` Each instance describes a single sequence step through its attributes definitions `RelatedProcess` and `RelatingProcess`, the successor and predecessor tasks respectively.

At present, the implemented tool enables a single construction schedule to be developed, visualised and then written to the IFC file relating to a given structural design. However, the IFC data structure has the facility for multiple schedules to be associated with a single design. This potential could be leveraged to enable alternative schedules to be developed and compared within the 4D planning environment of 4DAR, encouraging comparative and collaborative working practices to be harnessed during the project planning process.

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APPENDICIES

Appendix 1

This appendix section provides further information regarding the operational concepts of the 4DAR prototype not included in the main text.

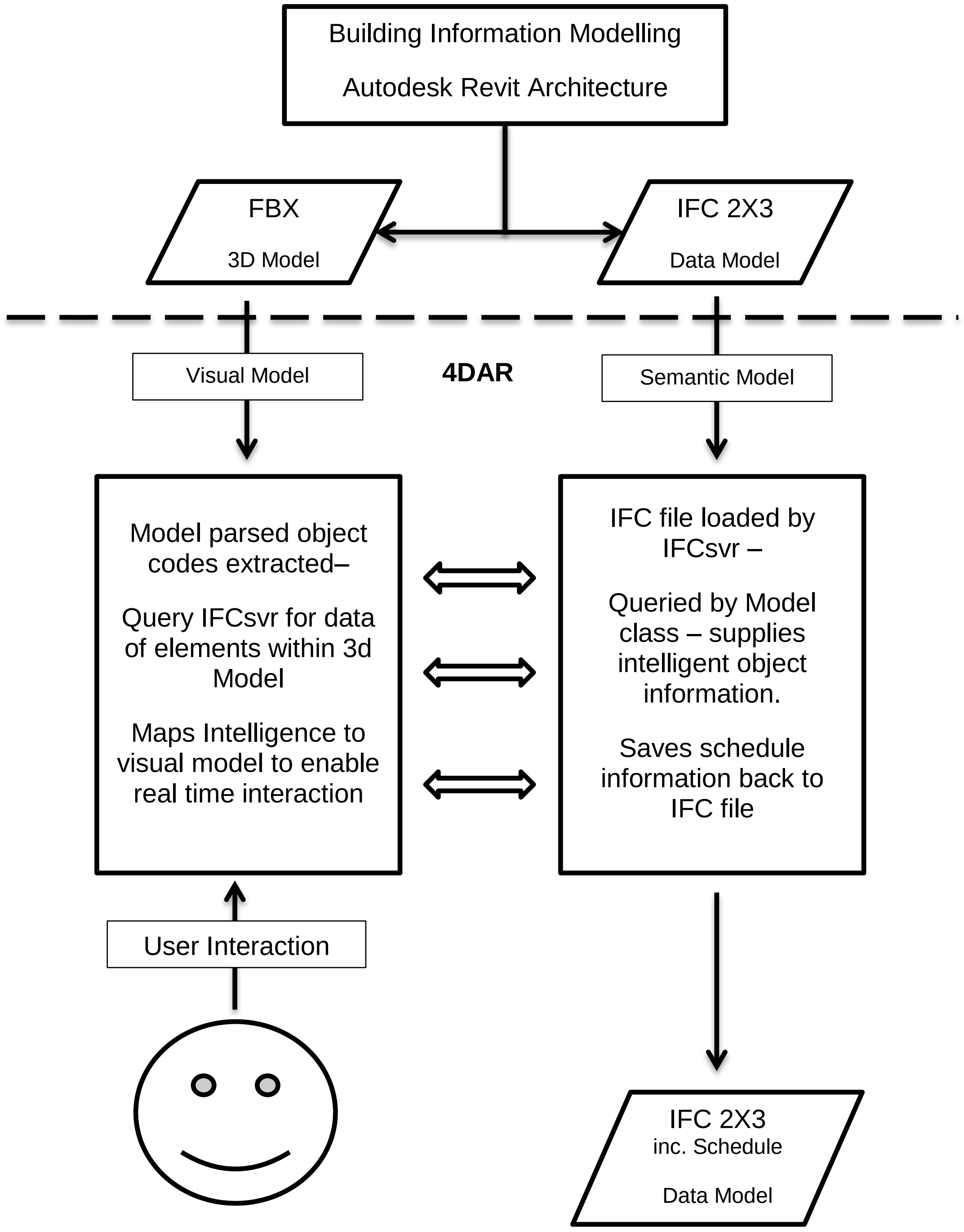


Figure 0-1 Data flow and specification

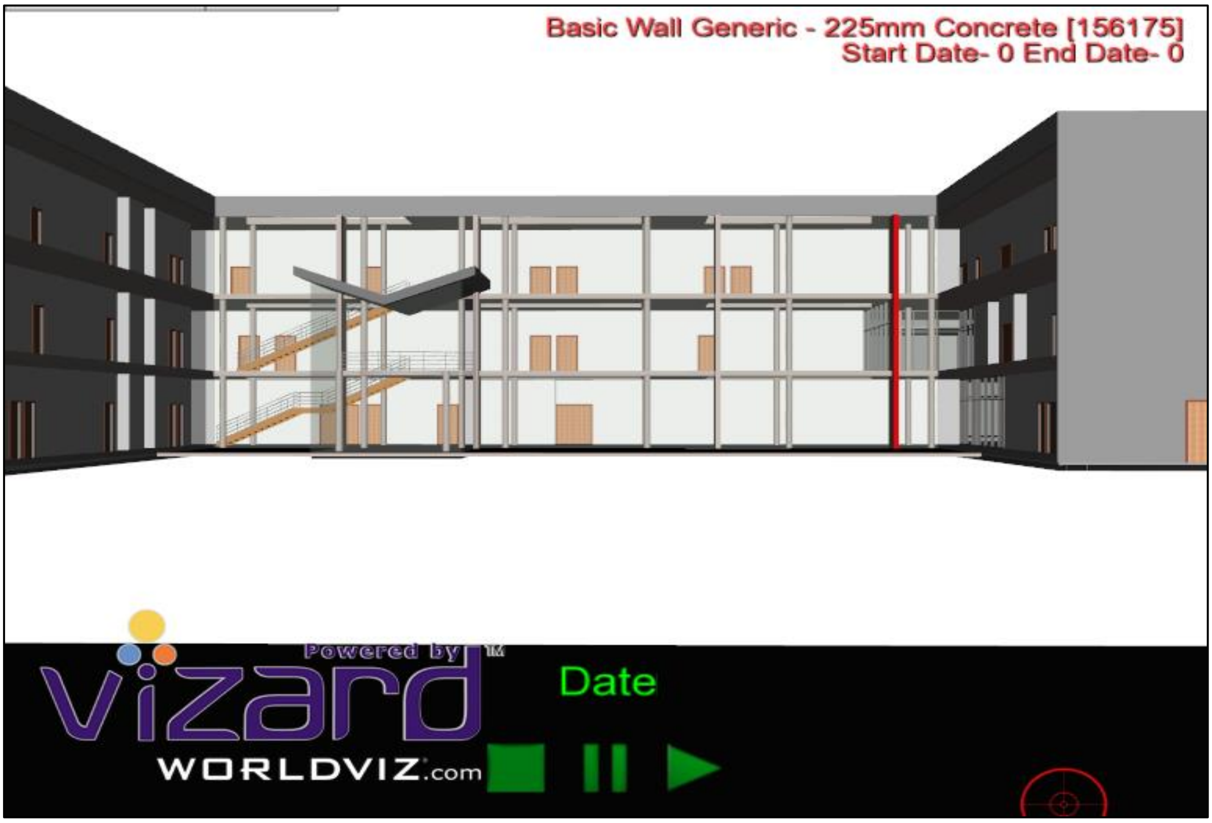

Basic Wall Generic - 225mm Concrete [156175]
Start Date- 0 End Date- 0

Figure 0-2 Single object selected

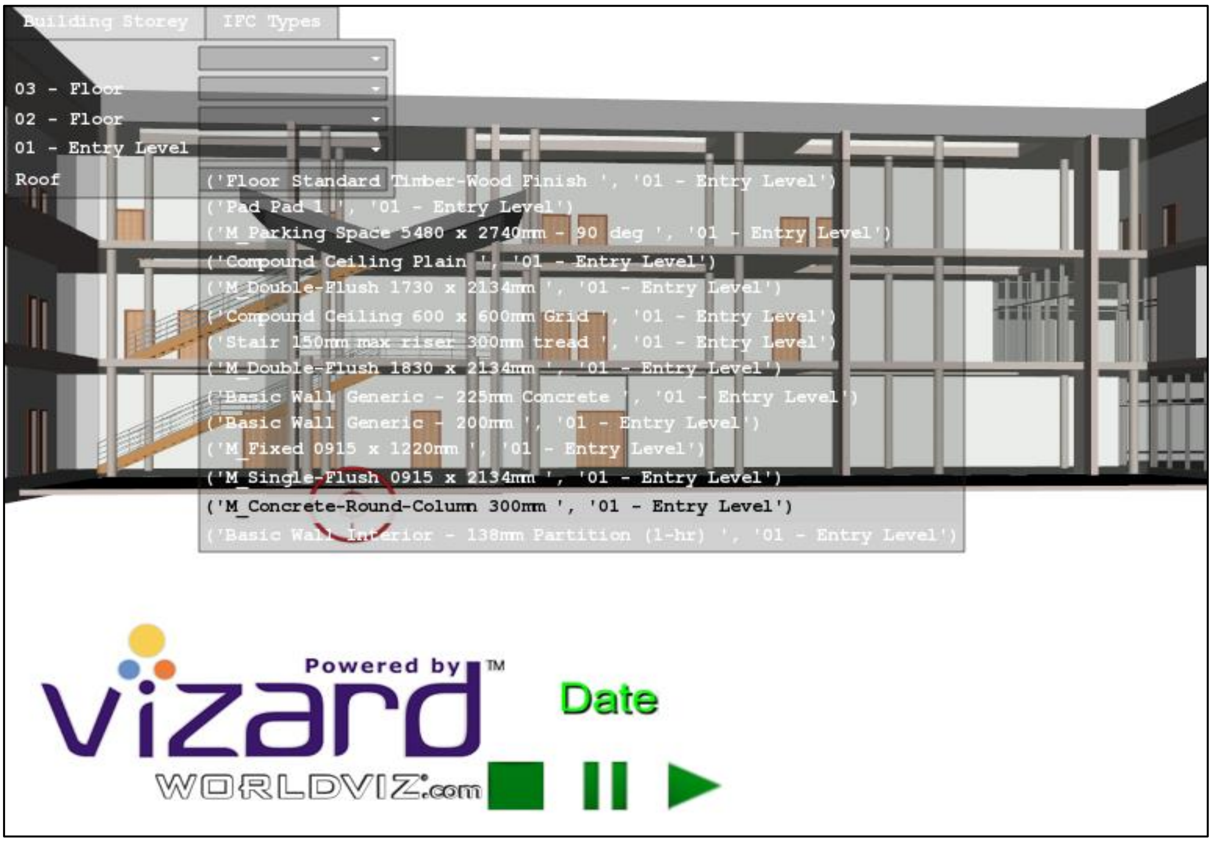
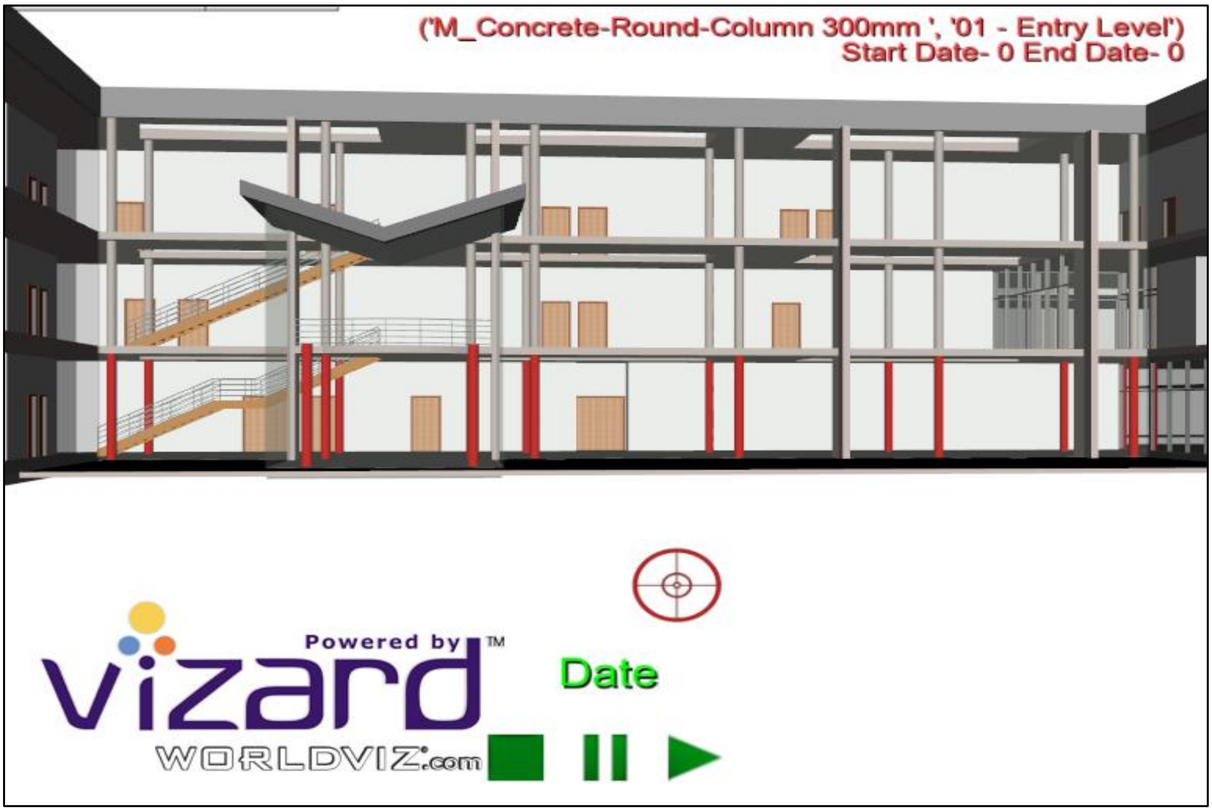
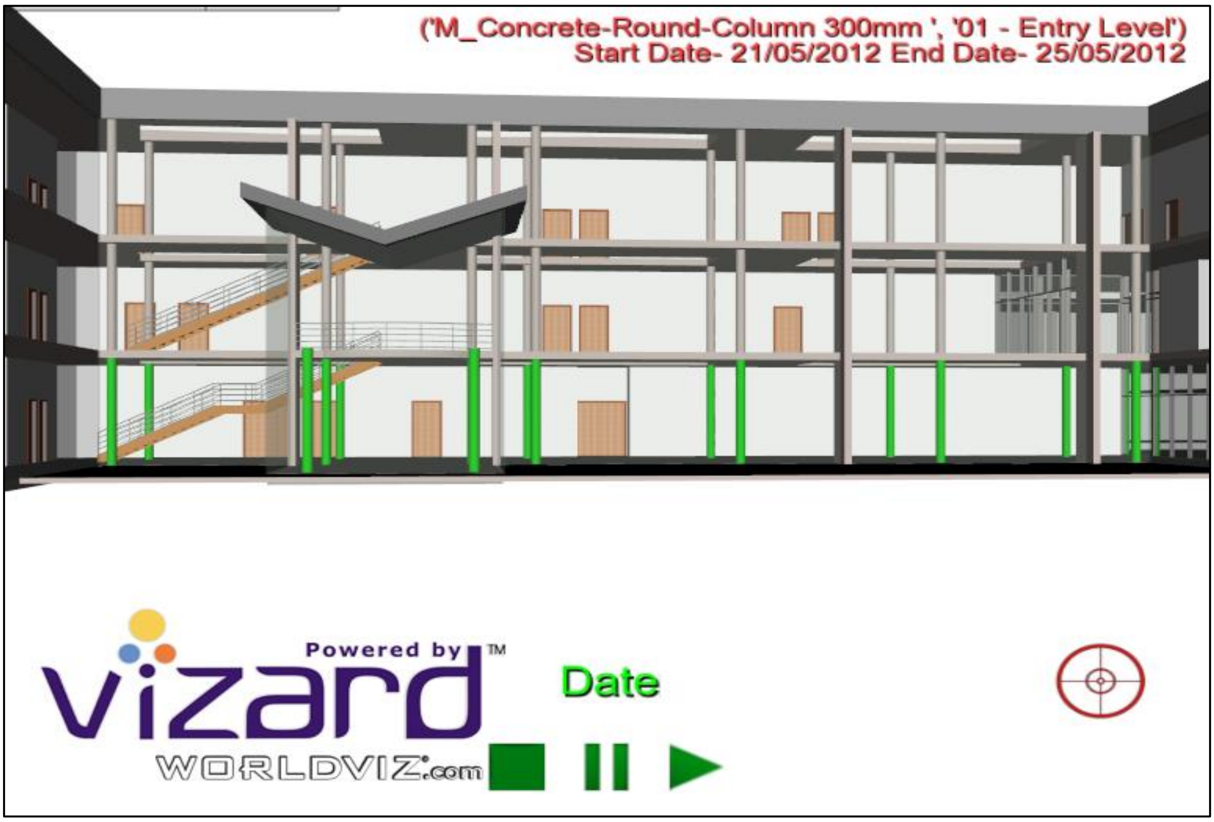


Figure 0-3 Menu selection for all Type on a particular storey



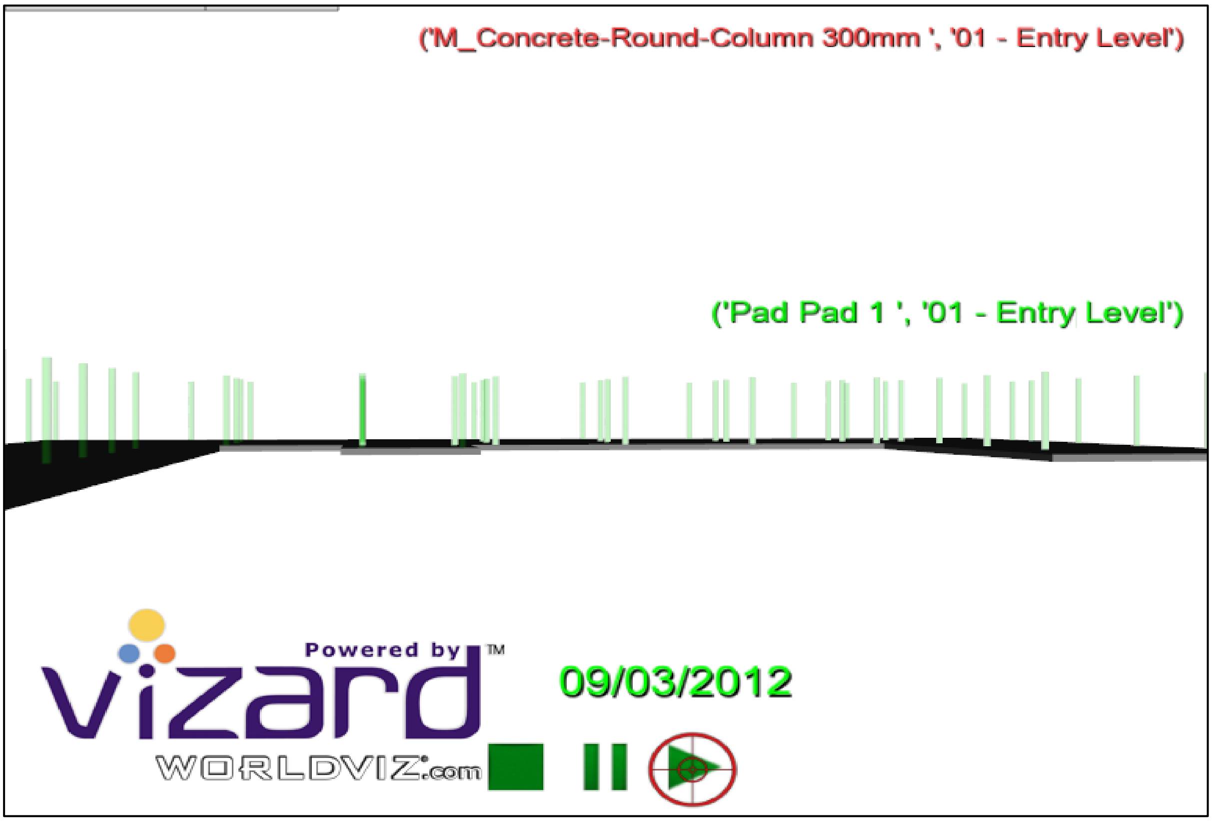
('M_Concrete-Round-Column 300mm ', '01 - Entry Level')
Start Date- 0 End Date- 0

Figure 0-4 All columns on 1st storey selected - no date assigned



('M_Concrete-Round-Column 300mm ', '01 - Entry Level')
Start Date- 21/05/2012 End Date- 25/05/2012

Figure 0-5 Items go green when date assigned to construction task

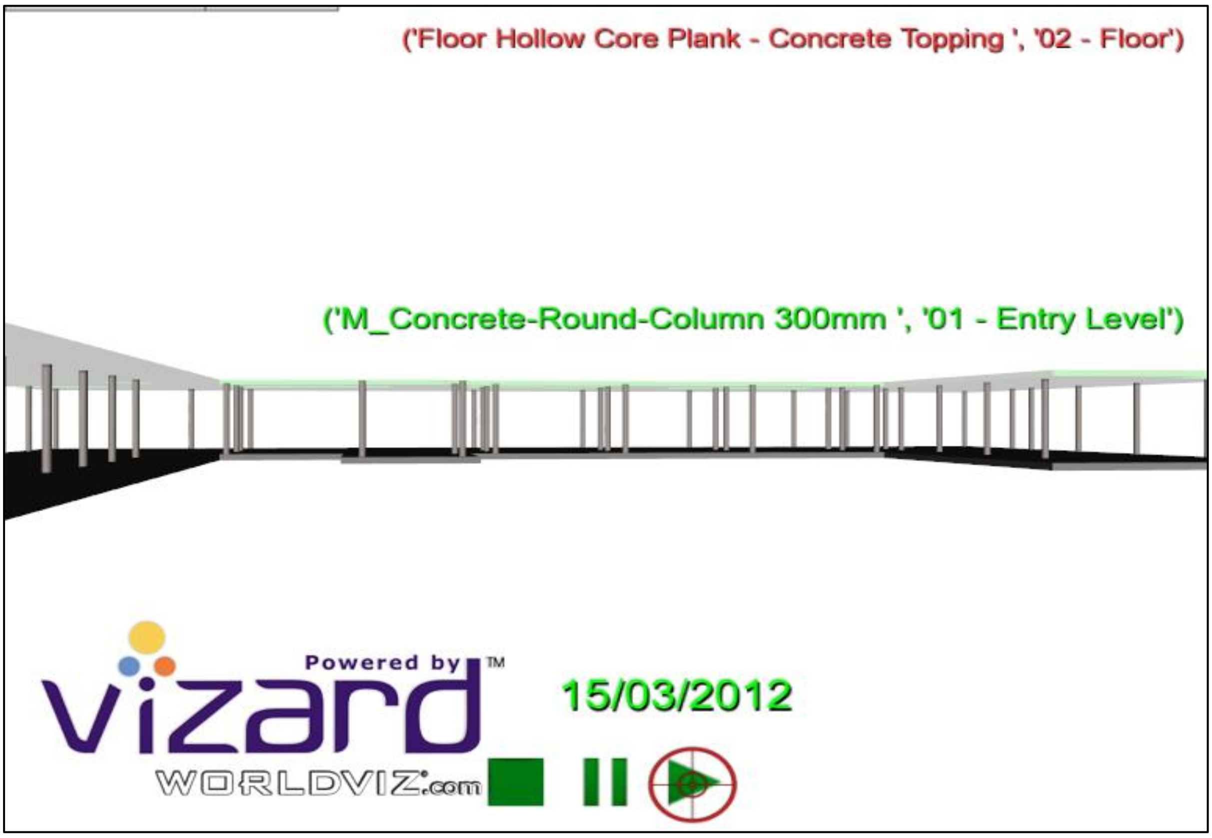


('M_Concrete-Round-Column 300mm ', '01 - Entry Level')

('Pad Pad 1 ', '01 - Entry Level')

09/03/2012

Figure 0-6 4D visual simulation showing just completed tasks (green) and tasks underway (red)



('Floor Hollow Core Plank - Concrete Topping ', '02 - Floor')

('M_Concrete-Round-Column 300mm ', '01 - Entry Level')

15/03/2012

Figure 0-7 4D visual simulation continued

Figure 0-8 Outdoor 4DAR scheduling session - selecting type by storey

('Wall Foundation Bearing Footing - 900 x 300 ', 'T/FDN')
Start Date- 0 End Date- 0

Figure 0-9 Outdoor 4DAR scheduling session – foundation bearing selected

('Wall Foundation Bearing Footing - 900 x 300 ', 'T/FDN')
Start Date- 01/10/2012 End Date- 04/10/2012

Figure 0-10 Outdoor 4DAR scheduling session - tasks date assigned to object

('Basic Wall Foundation - Concrete (417mm) ', 'T/FDN')
Start Date- 0 End Date- 0

Figure 0-11 Outdoor 4DAR scheduling session – single object manually selected

('Basic Wall Foundation - Concrete (417mm) ', 'T/FDN')
Start Date- 04/10/2012 End Date- 09/10/2012

Figure 0-12 Outdoor 4DAR scheduling session - date assigned

('Basic Wall Exterior - Brick on Block ', 'Level 1')
Start Date- 0 End Date- 0

```
('Basic Wall Interior - Partition (92mm Stud) ', 'Level 1')
('Floor Finish Floor - Wood ', 'Level 1')
('M_Fixed 750mm x 2200mm ', 'Level 1')
('M_Single-Flush 0762 x 2032mm ', 'Level 1')
('Basic Wall Exterior - Brick on Block ', 'Level 1')
('Floor 127mm Slab on Grade ', 'Level 1')
('Compound Ceiling Gypsum Board ', 'Level 1')
('Floor 150mm Exterior Slab on Grade ', 'Level 1')
('M_W-Wide Flange W310X60 ', 'Level 1')
('M_W-Wide Flange W410X60 ', 'Level 1')
('M_Single-Glass 1 0813 x 2420mm ', 'Level 1')
('M_Fixed 4835mm x 2420mm ', 'Level 1')
('M_Single-Flush 1250mm x 2010mm ', 'Level 1')
('Basic Wall Party Wall - CMU Residential Unit Dimising Wall ', 'Level 1')
('Floor Finish Floor - Ceramic Tile ', 'Level 1')
('Basic Wall Interior - Furring (152 mm Stud) ', 'Level 1')
('Stair Residential - 200mm Max Riser 250mm Tread ', 'Level 1')
```

Figure 0-13 Outdoor 4DAR scheduling session -

('Basic Wall Exterior - Brick on Block ', 'Level 2')
Start Date- 15/10/2012 End Date- 19/10/2012

Figure 0-14 Outdoor 4DAR scheduling session - further through the scheduling process

Nothing selected:

Figure 0-15 Outdoor 4DAR scheduling session - Select all objects of a particular type

Appendix 2

User Evaluation Survey Documentation