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VIRTUAL REALITY-BASED CLOUD BIM PLATFORM FOR INTEGRATED AEC PROJECTS

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SUMMARY: *Building Information Modelling (BIM) has demonstrated the need for integrating collaborative design teams' "project data", to not only help coordinate the design, engineering, fabrication, construction, and maintenance of various trades, but also facilitate project integration and interchange. Numerous potential benefits have inspired several countries to consider the implications of implementing BIM Level 3 (Cloud) as an innovative way of further enhancing the design, management and delivery process, ergo - a paradigm shift towards Integrated Project Delivery (IPD). Amongst the myriad of the available innovative approaches, web-based platforms are particularly beneficial for integrating visualisation components to give continuous sharing of relevant information for geographically dispersed end users. This study presents a game environment supported by a web-based Virtual Reality cloud platform for integrated AEC projects. This paper further explains the adapted Unified-Software-Development-Process of specifying this cloud computing platform, which employed iterative phases of Elaboration, Construction and Transition. This study presents new understanding and insight into the causal drivers and influences associated with successful decision-making design in non-collocated design teams. Research findings form a stepping-stone for developing new relationship models in collaborative environments, particularly gaming interfaces.*

KEYWORDS: *BIM, Cloud Computing, Design, IPD, Virtual Reality, Game Interfaces.*

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1. INTRODUCTION

The fragmented nature of the Architecture, Engineering, Construction (AEC) industry is well recognised, the consequences of which have led to several documented problems relating ostensibly to failures in communication and information processing (Egan, 1998; Latham, 1994). These failures have contributed to an increased proliferation of adversarial relationships between the different parties involved in a project (Forcade et al., 2007), which has also affected the veracity of design information (Cera et al., 2002; Fruchter, 1998) within the project lifecycle. In essence, the nature and complexity of communication within AEC projects has changed significantly over the last ten years, especially with advances in technology, and the increased prevalence of web-based project collaboration technologies and project extranets. Within the AEC sector, Information and Communications Technology (ICT) has revolutionised production and design (Cera et al., 2002), leading to dramatic changes in terms of labour and skills (Fruchter, 1998). In addition, it is also important to acknowledge that the capabilities of such applications (and implementation thereof) for predicting the cost and performance of optimal design proposals (Petric et al., 2002) could ostensibly enable designers to compare the quality of the proposed design solutions against other alternatives. This was reinforced by Goulding and Rahimian (2012), regarding the ability to experiment and experience decisions in a 'cyber-safe' environment, in order to mitigate or reduce risks prior to construction. Consequently, the success of AEC projects is highly dependent upon the type, level and quality of the innovative communication exchange between various disciplines involved in the design and implementation phases.

The success of AEC projects is highly dependent on the decisions made during early conceptual design and planning processes where 70-80 per cent of the production overheads (Paulson, 1976) are incurred. Among the tools for supporting advanced design planning include data-rich models (e.g. Building Information Modelling) - (initiated by Eastman et al., 1974; Fischer, 2000) allowing design teams to coordinate the fabrication of different building components. This created innumerable advantages, particularly in advanced methods of construction such as off-site construction, including faster delivery, improved economic indicators, along with improved sustainability factors and enhanced safety measures (Nawari, 2012). Isikdag and Underwood (2010) defined BIM as the information management process throughout the lifecycle of a building which focuses on collaborative use of semantically rich 3D Building Information Models (BIMs). BIMs contain rich geometric and semantic information about a building where different views/sub-models (e.g. Design, HVAC, FM) from them can be derived depending on the business need. Seminal literature has highlighted that BIM can revolutionise the whole AEC industry by: enhancing team collaboration (Gu & London, 2010); improving project integration (Woo et al., 2004); leveraging better construction information flow (Ibrahim et al., 2004); helping documentation flow (Popov et al., 2006); supporting facility management and reducing building maintenance costs (Wang et al., 2013); and providing construction simulation for teamwork planning, clash prevention and coordination interface (Fischer & Kunz, 2004). In line with this, the UK Government announced its "Government Construction Strategy" which included a mandate for the implementation of BIM Level 2 on all public projects by 2016 (BIM Task Group, 2013). BIM Level 2 indicates that a digital building model would need to be shared/exchanged between parties in the design/construction process which enables 2D/3D spatial coordination based on BS1192:2007.

However, several countries worldwide acknowledge a significant gap exists between this aim and their current situation. For instance, a survey conducted by the Malaysian Construction Industry Development Board (CIDB) in 2005 highlighted the lack of interest in using new integrated and/or parametric design tools for building projects among architects. Some later studies identified that this was due to the weakness of CAD-supported tools in supporting the intuitive design process that architects preferred in the early stage of the design lifecycle (Rahimian & Ibrahim, 2011). This creates a gap at the beginning of the iterative cycles of design process where designers often handle numerous repetitive building components with almost similar embedded information in them (Pour Rahimian et al., 2011). This study presents a need to support the multi-dimensional data-rich modelling process through comprehensive (integrated) Computer Aided Design (CAD) systems in order to deliver effective integrated projects.

One emerging issue is maintaining automation within the project lifecycle (Frohm et al., 2008; Skibniewski, 1992); which may for example include advanced manufactured construction with high product variety and significant variations in demand (Veenstra et al., 2006; Wikberg et al., 2010); or flexible and reconfigurable manufacturing systems (Colombo & Harrison, 2008), with effective/cohesive supply chains (Arif et al., 2005) – which includes integrated, web-mediated and automatic modelling, simulation and decision support systems (Fruchter, 1998). On this theme, Gu and London (2010) asserted that this was unlikely to happen unless construction information was represented and managed throughout all stages of the project lifecycle, including early conceptual design and planning processes. However, previous efforts on BIM have not really covered operation of such systems as an overarching integrated design and implementation platform. Ibrahim and Pour Rahimian (2010) acknowledged this gap due to the fact that conceptual design automation systems are still in their infancy, and that the existing CAD interfaces entail a lot of modelling and visualisation skills from the designers (which can hamper design creativity by interrupting the intuitive design reasoning when the designers need to concentrate on the cumbersome process of form generation using these complicated interfaces). As such, designers still prefer to produce their design ideas using traditional pen and paper based media - leaving the results to some others to create digital versions of their design solutions through a completely separate process (Pour Rahimian et al., 2008). This ostensibly causes various problems with respect to interoperability (Santos, 2009) of data between various teams of designers due to platform disintegration (Fruchter, 1998). A viable solution for automating conceptual design stages (and consequently streamlining the integration of the whole design process), is therefore needed. Lee et al. (2013) advocated the potential of parametric design interfaces as a new paradigm in the field of CAD, focusing on the potential of digital interfaces for producing design alternatives controlled by certain rules or limits, regardless of modelling and visualisation skills of designers. This approach has been praised for improving design creativity by allowing designers to use synectics as an idea seeding technique (Blosiu, 1999), while supporting the design process through the unproblematic generation of design alternatives (Kim & Kang, 2003). Cognisant of these approaches, this study developed a game-like (an interactive rule-based system which is capable of being controlled by multiple users in real-time) parametric site simulator tool using a web-based virtual reality interface, in an attempt to support a cloud BIM platform for integrated AEC projects.

2. CLOUD BASED BIM IN AEC AREAS

BIM is a model-based design process that adds value across the entire lifecycle of the building project (Autodesk®, 2011). It is an intelligent integrating modelling tool for building design and construction, which allows data sharing with all the stakeholders. It has been advocated that the key to implementation of BIM as the principal design delivery method is the ability of the various team members to easily share building information data during the design and construction processes. The information contained in a BIM model comes in various formats, thus it needs to be exchanged in an efficient way (Santos, 2009). Exchanging data can often be a challenge due to software incompatibility, different specifications, categorisation, format requirements etc. However, addressing these issues can create interoperable systems that can help data modelling migrate between different teams with minimal data loss and with improved optimal accuracy (Fruchter, 1998).

Conventionally, prior to BIM adoption, architects created three-dimensional models merely for visualisation purposes, and not using them as data-rich intelligent models. In ideal practice, BIM models are even capable to support information exchange amongst various team members. In this form, BIM is not any more a production tool, but a communication and social networking tool for designers. Succar (2011) explained various stages of BIM adaptation by introducing three major levels, namely modelling, collaboration and integration. The Australian Institute of Architects (2009) allocated the traditional production of two-dimensional documentation as stage zero in modelling implementation stages, thus rendering four capability stages in BIM all together. Australian Institute of Architects (2009) proposed a model to divide these stages into two sub-divisions, making each stages more specific in defining its capability. According to this model, BIM level one which is defined as three-dimensional modelling (stage 1A) and intelligent modelling (stage 1B). Intelligent modelling also includes data attached to it, whilst three-dimensional modelling is merely for visualisation purposes only. BIM level two refers to the ability of two or more computer systems or software applications to exchange the format by following a standard and to make use of the information delivered. It is frequently defined as an interoperability system that allows the user to respond to the delivered model and customise it based on its requirements, specification and needs by utilising the nD's modelling concept - 4D; time, 5D; cost, and 6D; facility management.

BIM can be considered more than a representation tool or a means for developing a model or prototype to generate intelligent input. Additional benefits embrace several other issues, including: facilitating the project teams to engage in innovative contractual relationships and new project delivery strategies. BIM level three offers an innovative way to excel in construction management. This new paradigm is known as Integrated Project Delivery (IPD). Here, the goal was to create a team effort to increase good communication and team's integration while working towards a consensus basis. This is often called as the future of BIM. On this theme, Santos (2009) asserted that amongst all barriers for achieving this goal was the interoperability problems of BIM.

Interoperability refers to incompatibility between inter-products and software applications. Incompatibility means that vendors have created a solution to this by having a BIM model converted into a neutral object-based file format; i.e., a format that is not controlled by any particular vendor, thus it can become a platform to exchange data. In essence, interoperability refers as the ability to exchange/share information between separate computer programs without any loss of content or meaning (Aranda-Mena & Wakefield, 2006). According to Succar (2009), interoperability is a linear workflow that allows the inability of simultaneous interdisciplinary changes to be shared in a single file-based sharing.

In the single operational file-based sharing model (Succar, 2009), once the building information model (1) is complete, it can be exported to the inter-operable model, BIModel (v1) to allow another process of modelling to be taken. This inter-operable model (v1) captures both geometry and properties of BIModel (1), thus facilitate the sharing of information. Then, this inter-operable model (v1) will be imported to the BIModel (2) to allow modelling process to take place; this procedure will be repeated for another modelling process until the project is completed. The capability of this interoperability system allows BIM to take one further step to improve the interdisciplinary collaboration among the project team. This could be considered as a stepping stone for web space-based platforms which are particularly beneficial for integrating visualisation components to give continuous related information sharing for the geographically dispersed end users.

One of the most referred industry (IEEE-1516) standards for large scale modelling and simulation is the High-Level Architecture (HLA) which was originally introduced by the U.S. Department of Defense (Kuhl et al., 2000). Zhang et al. (2012) advocated this system as it could integrate various simulation applications, providing a standard architecture for interconnectivity, interoperability and reusability. Uygun et al. (2009) also posited that by integrating various approaches and applications in computer simulations (using a unique framework, functional rules and common interfaces), could support flexible distributed simulations; moreover, could contribute to the reduction of software costs by supporting the reuse of simulation models and providing an infrastructure for managing the runtime of the simulations.

From a similar point of view, Wang et al. (2014b) proposed a structured methodology for integration of Augmented Reality (AR) technology to BIM, in order to overcome the issues related to limited sense of immersion and real-time communication of BIM within virtual environments. In a related attempt, Wang and Dunston (2013) developed a tangible mixed-reality interface to facilitate non-collocated collaboration for problem-solving and design error detection and Abrishami et al. (2013) proposed adopting Generative Algorithm to BIM to leverage its integration to conceptual design phases. Hou et al. (2013) developed another platform for controlling building components assembly procedures in order to improve accuracy and reduce errors. Wang et al. (2014a) adopted a more overarching approach and advocated the need for development of a computer-mediated remote collaborative design support system to leverage distributed cognition and help capture the non-collocated team's knowledge which is distributed in memories, facts, objects, individuals, and tools.

This research extends the findings of previous studies in this area, with specific emphasis on supporting the decision-making process at the construction stages through the development of interactive and interoperable simulation platforms. The study provides a novel approach to support non-collocated design teams using Game-Like VR environments blended to Social Sciences Theory (social rules) and Behavioural Science Theory (Decision Science/Communication Science). In essence, the aim of this study was to provide a flexible, interactive, safe learning environment for practicing new working conditions with respect to offsite production (OSP) in general, and Open Building Manufacturing (OBM) in particular; without the do-or-die consequences often faced on real construction projects. Hence, a VR interactive learning environment was sought which builds upon the multi-disciplinary practice-based training concept (Alshawi et al., 2007). In this context, the prototype aimed to enable disparate stakeholders, with different professional specialisations, to be exposed to the various aspects of OSP concepts. This approach was adopted in order to help overcome the problem of 'compartmentation' of knowledge (Mole, 2003). Furthermore, the prototype had to be flexible enough to allow any-time-any-place learning, so as not to be constrained to a particular place or time for learning to take place. This paper presents the system development features and the capabilities of the developed Web-Based Game-Like VR Construction Site Simulator (WWGVRSS).

3. APPROACH

Wellings and Levine (2010) noted that the high level use of game technologies in emerging educational schemes had already become an indispensable part of the next generation's lives in modern societies. Literature highlights various benefits of using advanced digital media in education. Wellings and Levine (2010) also suggested transforming existing text based lessons into problem-based learning platforms in which the training takes place via collaboration for development of solutions for real world problems. They argued that this is possible only with using immersive visualisation and simulation environments embedded in games and interactive interfaces for increasing engagement of trainees and trainers. From a similar point of view, Thai et al. (2009) argued that educational digital games can offer an intact opportunity to empower trainees' engagement and help transform teaching and learning into a new stage. ACS (2009) summarised the benefits of the currently developed interactive game-like immersive environments as follows: 1) exploring knowledge by clicking on objects with linked information, 2) strengthening of education by providing a repository of aids, tools, etc., associated with nD objects, 3) offering collaborative workspaces, e.g. nD informal discussion forums, 4) traditional instructor-based education via a distance delivery method and, 5) simulated learning by modelling a process or interaction that closely imitates the real world in terms of outcomes. With respect to construction industry, Su et al. (2013) advocated using VR and game environment for supporting training of construction equipment operation which not only facilitates hands-on practice (as a vital component this type of training), but also prevents the risks of personal injury and equipment damage and eliminates the cost of fuel and site, and assignment of training personnel.

Similarly, the aim of the development of this WGVRSS was to embrace 'real life' issues facing OSP construction projects in order to appeal to professionals by engaging and challenging them to find 'real life' solutions to problems often encountered on site. Hence, a real construction project was used to govern the authenticity of the learning environment. In this context, the prototype learning simulator would allow 'things to go wrong', and hence, allow 'learning through experimentation' or 'learning by doing'. In this respect, although the 'scenes' within the simulator take place on a construction site, the target audience is focussed primarily on construction professionals e.g. project managers, construction managers, architects, designers, commercials, suppliers, manufacturers etc. Thus, the construction site was used as the main domain through which all the unforeseen issues and problems (caused through upstream decisions, faulty work etc.) could be enacted, so that real implications could be better appreciated in respect of time, cost, resources etc. In this context, learning occurs through the following:

- Learner autonomy - to make all decisions;
- Interactivity - environment provides feedback on the decisions taken, and their implications on the overall project (cost, time, resources, health and safety, etc);

Reflection - users are able to defend decisions on the feedback provided, and have the ability to identify means to avoid/mitigate potential problems in the future such as: 1) OSP strategies e.g. Design for Manufacture Logistics and Assembly (DFMLA), 2) Business processes, procurement/contractual arrangements, project management, quality assurance etc., 3) Health and Safety procedures, 4) Supply chain integration, 5) New manufacturing technologies, open system, etc.

3.1 VR Simulator Development Concept

The main concept of the simulator is based on its ability to run scenarios through a VR environment to address predefined training objectives. In this respect, learning is driven by problems encountered in this environment, supported by a report critique on learners' choices, rationale, and defence thereof. In this respect, the development encompassed two phases. Phase I embodied the development of the various scenarios, including the generation of reports etc; and Phase II, included the 'intelligence' components, including the interrogation of learners regarding their understanding, along with the assessment engine.

3.2 VR Simulator Development Framework

The simulator development framework encompasses four main activities: (identify training objectives; develop scenario(s); develop the VR environment; and validation of the prototype – see Fig. 1. This framework required extensive input from the construction industry in order to not only secure relevance, but also help govern authenticity of these stages.

3.2.1 Training Objectives

The main training objectives underpinning the simulator were gathered from a synthesis of seminal literature covering the potential risks and threats facing OSP in general, and Open Building in particular. The capture of this knowledge was seen as fundamental for learners to fully appreciate, as it helps form the basis of appreciating how different stakeholders deal with the implications of such problems; and consequently, help learn how these could be mitigated for future practice. In this context, seven risks were identified: 1) To encompass late design changes, 2) To embrace issues such as the loss of factory production, or production capacity, 3) To include unpredictable planning decisions and designs that are not suited to OSM, 4) To capture the issues associated with tolerances, 5) To include the potential of suppliers' failure to deliver on time, 6) To allow for manufacturer bankruptcy, and 7) To deal with issues associated with alternative manufacturers.

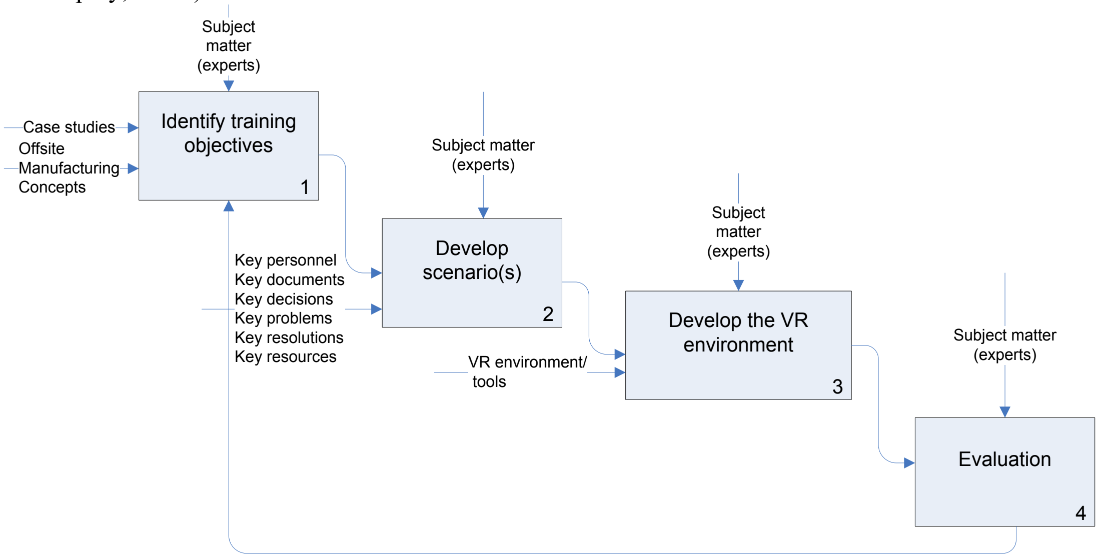


FIG 1: VR Environment Development Framework.

3.2.2 Scenario Development

The scenarios were developed in order to expose learners to new working conditions and issues that they were likely to face on real construction projects employing OSP concepts. Therefore, it was deemed important to challenge learners to think about the routes of these problems, rather than just reacting to them. This concept was used to provoke learners to think 'proactively' about future OSP projects. In this context, the main scenario was based on identifying all possible problems/issues that are traditionally associated with OSP practice. These are colloquially referred to as problem 1, problem 2, etc. Fig. 2 shows the sample situation in which Problem 1 accrues; as a consequence of Problem 1, the user is provided with a number of possible decisions. Every decision is associated with multiple actions to take. Depending on the action chosen, the programme schedule, along with corresponding costs, time, and resources are affected. The system them generates a report summarising all decisions made and how these relate to the learning outcomes.

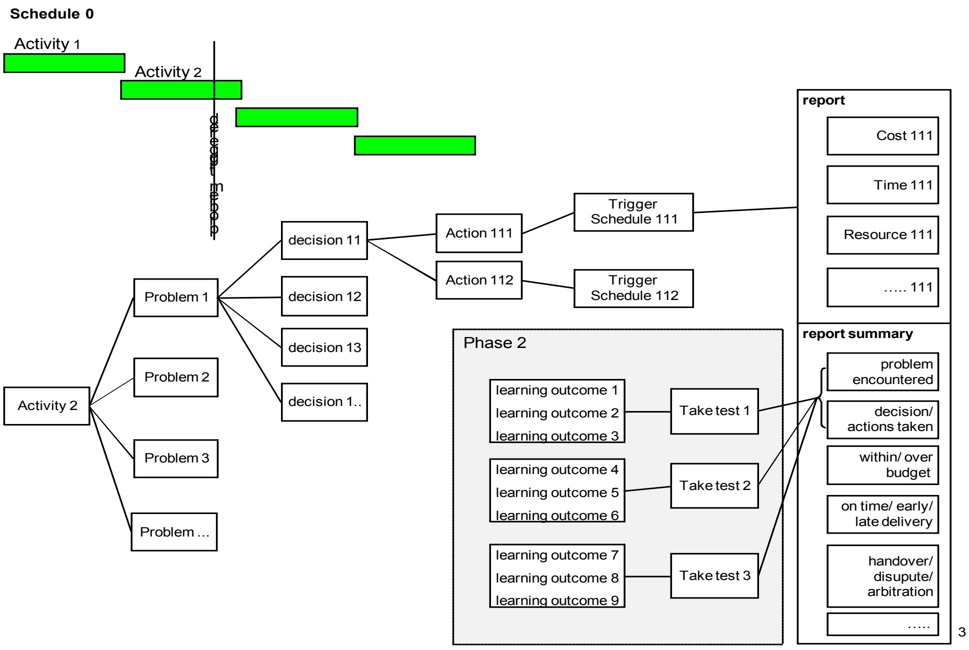


FIG 2: Scenario Implementation Concept.

These scenarios were used to simulate how OSP operates in real-life, in order to provoke learners to think 'how' and 'why' things may go wrong; and why consequently OSP may end-up being more expensive than the traditional way of working and thinking. As part of the learning process, learners are able to identify 'why' things went 'wrong', and 'how' these problems could have been avoided. Furthermore, a debriefing session is used to allow thorough interrogation of problems and choices selected, whereby learners are able to elaborate on the issues faced during the VR session; which helps to distinguish between 'being immersed' within the environment and the process of critical reflection that takes place outside the VR environment (De Freitas & Oliver, 2006).

To run a scenario, various information and data has to be input into the system in order to help populate the scenario. This data includes: a) Construction site type with respect to location and site scale, constraints, and layout b) Project type with respect to primary use of building (e.g. commercial or residential), budget allocated, type of structure, special layout and planning etc., c) Manufacturer type in terms of scope, capacity, location, costs associated and maintenance, d) Equipment hired in terms of size, capacity, assembly rate, required labour, hire rate etc., and e) work plan and associated possible interruptions/problems, including manufacturing option. This information is sourced from a predefined 'real' project and categorised in a relational database.

In essence, the simulator was expected to provide the learners with 1) simulation of site operations within real life and fast track time scales, 2) generation of reports based on all decisions made and their influences on project costs and risks, 3) saving and reloading sessions 4) running possible 'scenario directions/alterations' randomly based on the predefined interruptions and problems, 5) cross-examine learners' knowledge through transitions between different phases, 6) and generating feedback to learner on their performance. In accordance to these objectives, the Game-Like Virtual Reality Construction Site Simulator was designed and developed as an educational web-based simulation tool comprising of both non-immersive and immersive pages for providing novice construction managers with the opportunity of experiencing challenges of real-life AEC projects through simulated scenarios. In order to minimise interruption on the learners' reasoning process, the Graphical User Interface (GUI) was designed to be as simple and straightforward as possible with respect to data input. The interface was designed as to be accessible through any standard web browser. As presented in Fig. 3, at the first stage the interface provide users with login account details and helps the users retrieve their previous information or register as a new user.

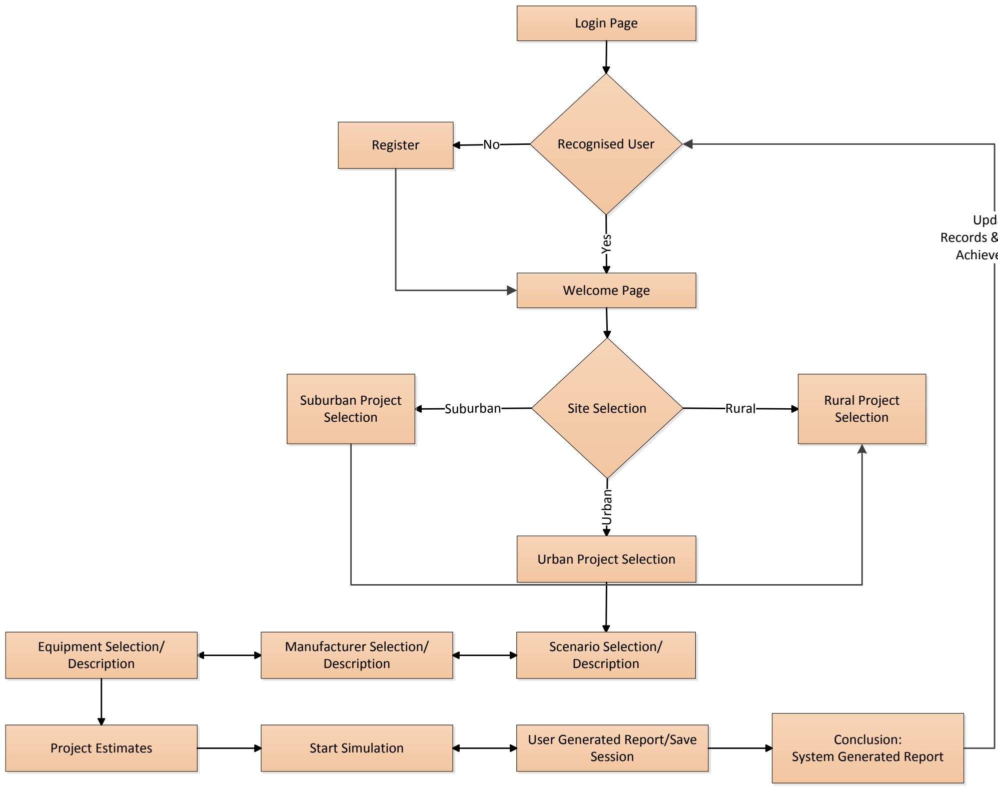


FIG 3: Workflow of the simulator HCI.

In the Welcome Page, the users are given information about the game, then other criteria, e.g. selection of available construction sites category (i.e. Rural, Suburban, and Urban Projects), different available projects in every category and the type of Scenario for the game (e.g. Late Design Decisions), and the list of qualified contractors and manufacturers available for every selected project. The trainees then make their selection on the list of equipment for their project and then they can see the project estimates to agree and proceed. All choices made by players as well as their registration data are then automatically recorded in MySQL database, which is also accessible through the immersive application for project simulation.

As presented in Fig. 3, following the Project Estimates session and after completing the initial decision-making process through the interactive ASP.Net Web Forms, learners are able to commence the 4D stimulated training session; i.e., starting with a 'walkthrough' to experience and appreciate the complexity of the project. At this stage, the application provides users with a summary of the project and contract, and runs the simulation of the project within an immersive and interactive environment developed in Quest3DTM VR programming Application Programming Interface (API). Within the Simulation environment, the users are able to experience the outcomes of all decisions made. They are also challenged by unexpected events designed according to the selected scenario, and are required to make decisions for dealing with these issues. The simulation runs in a fully immersive 3D environment, and users are able to navigate the whole interior and exterior spaces of the project site. At various points in the scenario, they are also able to interact with the different elements of the simulator in order to retrieve further information e.g. technical specifications, videos on selected OSP construction systems/details, project data etc. In order to keep the users in track of the project, the simulator also provides them with monitoring tools revealing the project time, latest assembled module, accumulative costs of the project, team communication etc. The monitoring and communication tools are embedded in different parts of the main interface as well as the facilitated standard embedded virtual PDA interface, which appears when required. The simulator ultimately records and tracks the users in the database and navigates to the conclusion page to reveal all scores of the user together with the logic behind the marking procedure. Table 1 presents the screenshots of the explained stages.

4. PROTOTYPE DEVELOPMENT

In the first stage of the prototype development lifecycle, the project established the requirements and priorities (from Phase 1), represented in an ontological structure. The generic structure and content for the knowledge objects then were formulated with wrappers using metadata. The next stage established object classes and their hierarchy to satisfy multiple abstractions (and compliance with extranet metadata). The final stage developed the user interface to comply with Human-Computer Interaction (HCI) protocols, and accessibility guidelines etc. in order to provide the system with a robust and reliable structure. The developed system includes simulated scheduling of the project, association of the 3D models and building blocks with project lifecycle, supply chain analysis monitoring for each building block or activity, management of delays in material delivery through sending emails to manufactory managers, and a final breakdown for project costs and labour.

4.1 System Architecture

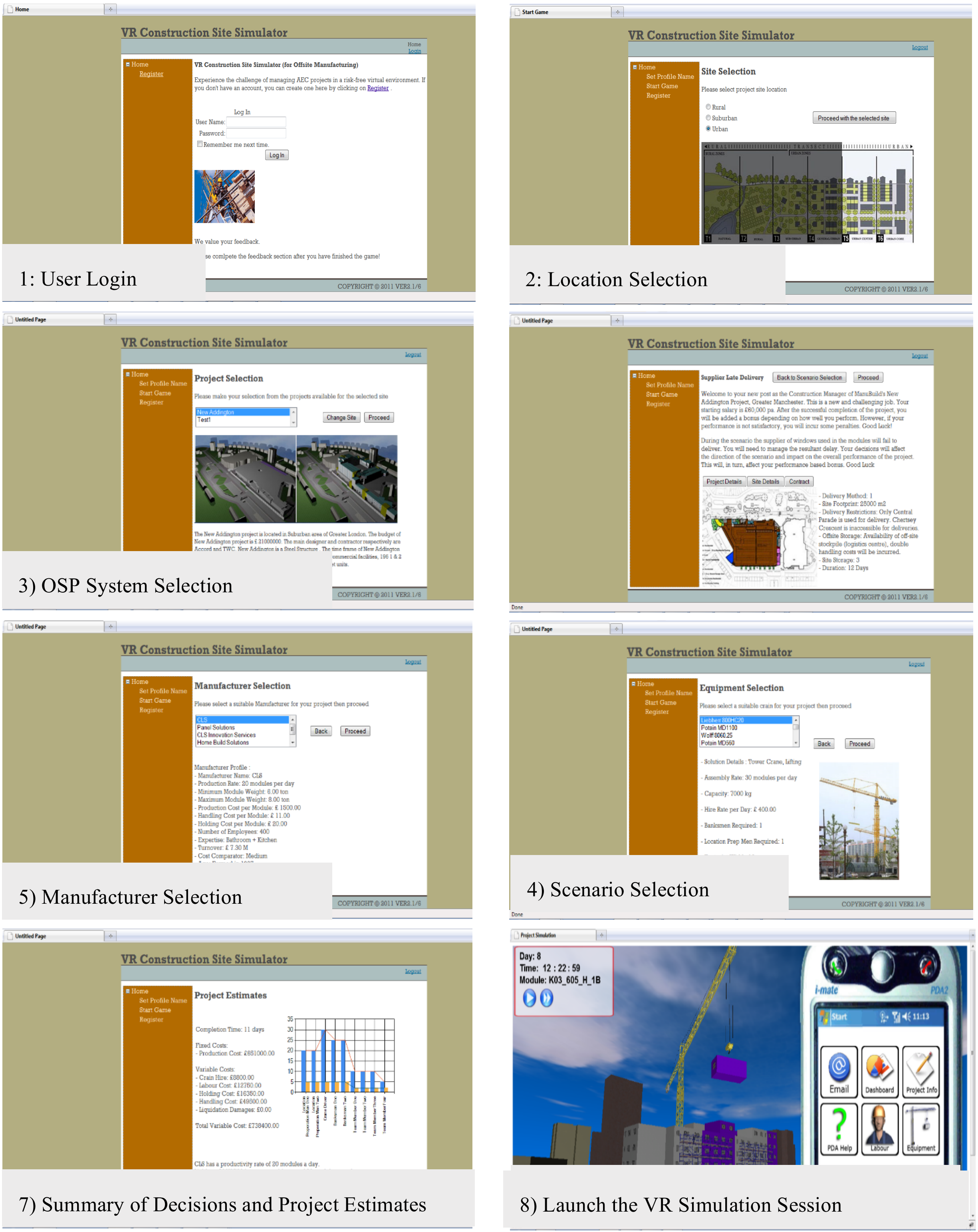
Existing VR interfaces have ostensibly been formed based on one single idea: creating 3D models and incorporating them with some pieces of information so that both 3D models and information are editable through an interactive real-time interface (Pour Rahimian & Goulding, 2010). Contrarily, they differ from each other based on their architecture and the utilised methods for data creation and retrieval. However, data creation and retrieval methods in VR interfaces can be investigated from two different perspectives, namely creating 3D bodies of constructional elements per se and defining characteristics of the elements.

Although, creating 3D objects directly in VR environments is not impossible, this is usually created in CAD applications; since doing so in VR is often cumbersome and time consuming. Consequently, current VR interfaces can be categorised considering how they convert CAD models into VR elements. In terms of transforming design elements from CAD into VR, there are three de facto approaches used by different practitioners. Whyte et al. (2000) noted three approaches for this translation as being: 1) Straightforward translation approach and importing the whole environment from CAD to VR; 2) Library-based approach and putting the elements of construction in the library of VR environment then calling them when and where necessary; and 3) Database-oriented approach with a central database for controlling the module characteristics. Here, the database utilises both CAD and VR environments as graphical interfaces. Therefore, the third approach can be characterised as a combination of computer graphics and web programming. The database-oriented approach was selected for this project, as it was the only way that could facilitate learners to have access to the system from multiple remote locations.

VR interfaces in the AEC industry vary also based on the method of manipulating the objects within the environment and the adapted programming method in VR interface. There are three major kinds of programming applications currently used by VR programmers as follows: 1) 3D Application Programming Interfaces (APIs); 2) Virtual Reality Modelling Language (VRML) and 3D web technologies; and 3) recent commercialised object oriented VR programming packages. In this respect, 3D Application Programming Interfaces (e.g., Open GL and Direct 3D) are principal environments for VR programming in C++ and Visual Basic. Falling in the category of computer graphics, they are capable to either create all models directly inside the space or/and import them from CAD applications. They are perfect environments for advanced programmers for creating Win32 console applications, which are used in developing computer games; however, integration of such interfaces with web programming is quite difficult and often leads to failures in cases of complicated works.

Virtual Reality Modelling Language (VRML) and 3D web technologies in their first version were made as a division of Open Inventor; thereafter, have become the international standard for 3D web modelling. These applications provide variety of facilities for manipulating immersive library based web interfaces; however, they lack the capability of integration with interrelated databases as they are not essentially database-oriented applications. Recent commercialised object oriented VR programming packages now contain built-in modelling environments for creating VR spaces directly or importing them from CAD applications. Such VR programming applications also contain logical libraries for defining behavioural links among the objects and simulating physical phenomena. Although the architecture of such applications is made based on APIs of C++, in some aspects they can offer a higher-level abstraction for programmers. Nowadays, there are three frontier commercial VR programming applications, namely Quest3DTM, EON RealityTM and VirtoolsTM. The outcomes of these applications are directly deployable into Visual C++ and Visual Basics web programming platforms (EON Reality Inc., 2008).

TABLE 1: VR Environment Initial Selection Screens



This makes them extremely flexible in terms of integrating VR programming (which is a part of computer graphics) with web programming and data mining. They also come with full Software Development Kits (SDKs) in order to help advanced programmers add some building-blocks and prototypes to create rationales or behaviours that were not originally provided by the application. Besides, the SDKs let programmers integrate their interfaces with particular VR I/O devices, e.g. Head-Mounted-Displays (HMDs) and data gloves. In this respect, this study proposed employing a database-driven approach using structured modelling phases and API based programming for the development stages. Linking 3D objects to datasets through a web environment for associating schedule of activities (4D visualisation), the system was able to optimise learning outcome through showing the changes in real-time.

Consequently, this study modelled all elements and components of construction site in either AutoCADTM or 3D Studio MaxTM as two of most the popular modelling software applications. The scenarios then were scheduled in MS ProjectTM environment. Moreover, all VR programming tasks were performed in Quest3DTM environment, whilst Active Server Pages (ASP.NetTM) web development tool using C# programming language was employed in developing the user interface. Finally, MySQLTM database which was compatible with both programming environments was installed on a server in order to track, manage, and transmit user data. The adapted Unified Software Development Process ultimately took the WGVRSS through an iterative testing procedure to diagnose and troubleshoot the prototype regarding functionality, compliance, grouping, integration, maintenance, version control, and validation, which incorporated amending the interface to include any additional fields/delimiters identified in Phase 1. In essence, the architecture of the proposed simulator was designed as shown in Fig. 4.

4.2 3D modelling of site elements in AutoCAD and 3D Studio Max environments

In this project system, AutoCAD and 3D Studio Max was employed as the geometrical modelling platforms. Different construction site elements including both permanent (e.g. structural/architectural element and building blocks) and temporary (e.g. scaffolds and site barriers) constructional objects were created in detail. Model for constructional machinery and operational elements (e.g. Tower Cranes and Trucks) were also downloaded from CAD forums and websites. In order to optimise the final system performance, the project created the models at a very primitive level (e.g. beams, columns, walls, building blocks) and left the final assembly for Quest 3D as the 4D Simulation tool in which regeneration and repetition of single models in geometrical arrays do not demand allocation of huge space on the graphical memory. For the same reason, the project used a lot of bitmaps to give the illusion of secondary details, rather than actually creating them in 3D models. The bitmaps also helped the simulation look more realistic by visualising texture of different materials (e.g. concrete, wood etc). Ultimately, the models were converted into 3DS file format (in order to be readable by Quest 3D) and saved together in the same folders as their respective bitmaps.

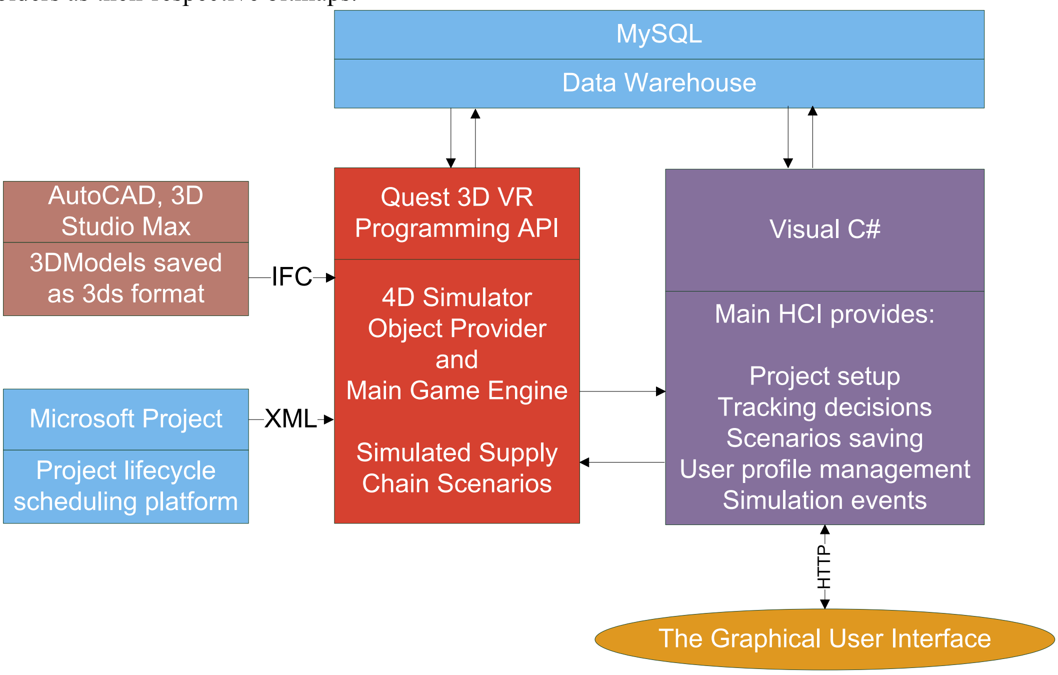
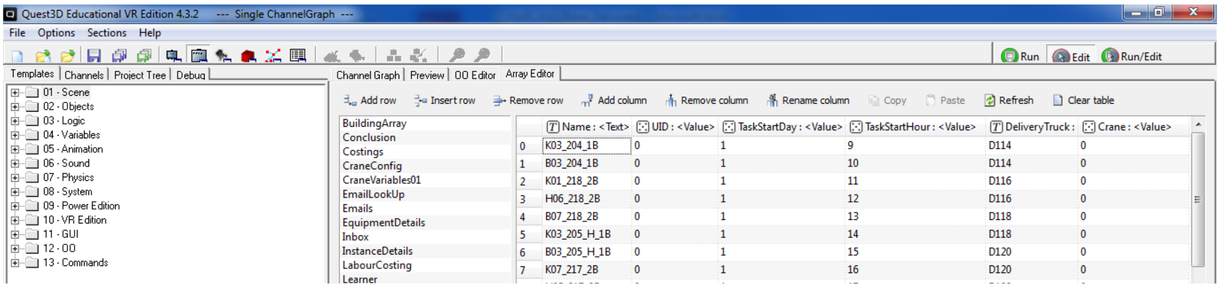


FIG 4: Simulator Architecture.

4.3 Project Scheduling within the MS Project^{TM} Environment

The study used MS Project software application for scheduling project lifecycle based on the developed scenarios. For each scenario, the temporal relationships amongst different assembly tasks were planned from the commencement of the project to the day of completion. In addition, it included random occurrence of some unexpected problems and interruptions during the project lifecycle. These schedules formed the essential basis for data regarding sequence amongst different assembly activities, duration of different constructional tasks and their commencement time and finishing time. Finally, the schedules were converted to MySQL databases which are accessible for both C# and Quest3D programming tools.

Fig. 5 shows a sample project array within Quest3D that is imported from MySQL. The presented array in Fig. 5 identifies the details of assembly of various building blocks in terms of the 3D position of the building block, sequence of assembly, exact delivery time, and the machinery involved in transportation and assembly of it. Since all these data were stored in a relational database, the pieces of information regarding costs and labour for both building blocks and equipment was also automatically associated to all tasks. Moreover, this made it possible for learners to modify or update scheduling data through ASP.Net interfaces.

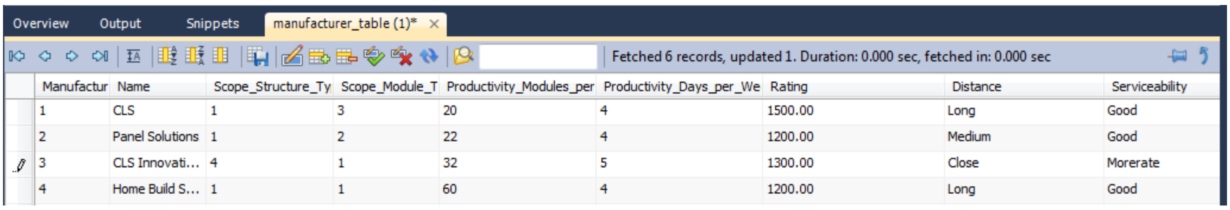


	Name : <Text>	UID : <Value>	TaskStartDay : <Value>	TaskStartHour : <Value>	DeliveryTruck :	Crane : <Value>
0	K03_204_1B	0	1	9	D114	0
1	B03_204_1B	0	1	10	D114	0
2	K01_218_2B	0	1	11	D116	0
3	H06_218_2B	0	1	12	D116	0
4	B07_218_2B	0	1	13	D118	0
5	K03_205_H_1B	0	1	14	D118	0
6	B03_205_H_1B	0	1	15	D120	0
7	K07_217_2B	0	1	16	D120	0

FIG 5: Sample Project Array within Quest3D Imported from MySQL Database.

4.4 Data Warehouse in MySQL^{TM} environment

MySQL was selected as the platform to host the databases of this project as it is the only application that provides Quest3D with Software Development Kit (SDK). It is also accessible in MS Visual Studio environment through Devart DotConnectTM and ADO.NetTM. Therefore, a relational database comprising of 44 different tables was created in MySQL to manage information regarding manufactures, equipment, labour and costs associated with different tasks, schedules for different scenarios etc. It provided the learners with full control on project data through both web forms and project simulation environment. Fig. 6 presents a sample table of different manufacturers data and criteria. As it could be in the Fig. 6, this table includes all sorts of information with regards to the manufacturers, in terms of the name of available the companies, the scope of their work and



Manufactur	Name	Scope_Structure_Ty	Scope_Module_T	Productivity_Modules_per	Productivity_Days_per_We	Rating	Distance	Serviceability
1	CLS	1	3	20	4	1500.00	Long	Good
2	Panel Solutions	1	2	22	4	1200.00	Medium	Good
3	CLS Innovati...	4	1	32	5	1300.00	Close	Morerate
4	Home Build S...	1	1	60	4	1200.00	Long	Good

the type of structure that they produce, the number of unites that they can deliver per day, the fees that they charge per unit, their distance to the selected project, and the level of customer satisfaction of the particular manufacturer.

FIG 6: Manufacturers' Information Table within MySQL environment.

4.5 Main Human Computer Interaction (HCI) interface with Visual C#

The designed ASP.Net interface using C# helps learners justify all project parameters and obtain the output as the simulated project site. The learners can also evaluate the details of potential assembly process throughout the planning procedure via the provided user interface. The designed simulator provides ASP.Net web forms as the initial GUIs that are used for transferring messages from users to the system in order to gather data regarding specifications of the desired construction process. Using these web forms, learners are able to control the type and sequence of construction tasks and make decisions on type and level of machinery involved in the project. The system also provides learners with estimates of project costs and time then proceeds to the simulation of the project. The simulation is generated in ASP.Net environment an embedded object by calling an external object exported by Quest3D. The embedded object is called by executing the following HTML code:

```
<body>
    <form id="form1" runat="server">
      <embed height="720" width="100%" checkupdate="1" type="application/quest" src="Quest3D_v59a.q3d"
documenturl=" ~/ index.htm" id="Quest3DObject">
      </form>
</body>
```

Based on the collective decisions during the planning process and simulation time, the system calculates the total costs of the project and provides comparison between the results and average of similar projects. The system then generates a detailed report on the performance of learners. Fig. 7 presents the C# code-behind and design interface of a sample project estimate associated with a chart generated through analysing data derived from project database. As it can be seen in the code behind shown in the right hand side screenshot, there are various string functions that retrieve the information of the project including type, category, productivity etc. from the project database, and these strings convert the data to visual presentations and show them in forms of histograms and tables indicating the breakdowns of costs and project key performance indicators in the main user interface (as can be seen in left hand side screenshot).

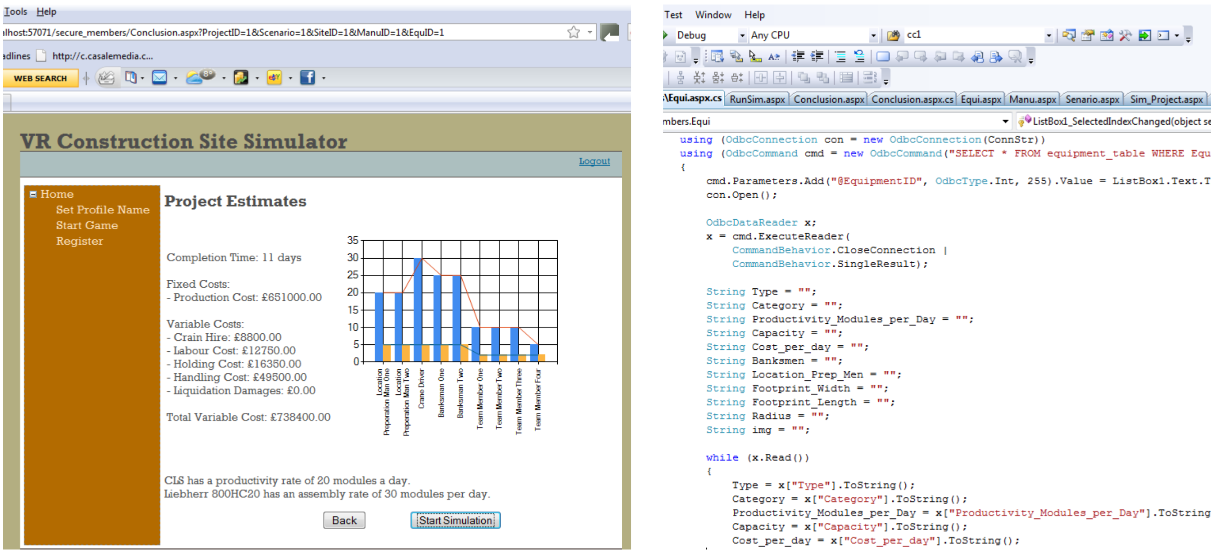


FIG 7: Design Interface (Left) and C# code-behind (Right).

4.6 Quest3D VR programming environment

The geometrical 3D models of the constructional elements were imported by Quest3D in order to provide the basic entities and building blocks of VR programming. Quest3D is an Object Oriented (OO) programming platform in which the programming logic is formed through interconnection of Logical Building Blocks. In this project, the structure of the programme comprised of four main components: 1) The static 3D models of construction site including tower cranes, trucks, land, surroundings, and supporting elements which do not change from one learner to another (e.g. scaffolds); 2) Building Blocks as the dynamic 3D models of project; 3) Project Schedules for controlling all events of assembly and delivery process; and 4) Monitoring tools for keeping control of project time and resources.

Fig. 8 presents the static elements connected to the interface, which were directly generated using 3DS and bitmap files (which appeared at particular locations). However, tower cranes and trucks were programmed to perform the desired animations at certain points of time. The modules of all static objects were directly connected to the project interface, except for those additional tower cranes and trucks that might or might not be hired by the learners. In these two cases, the modules were connected to the interface through an IF Toggle Channel in order to call the entities based on the preferences of user saved in the database. Another IF Toggle Channel was also connected to the main interface in order to facilitate switching the view into interior of Kitchens, Bathrooms, and Hallways.

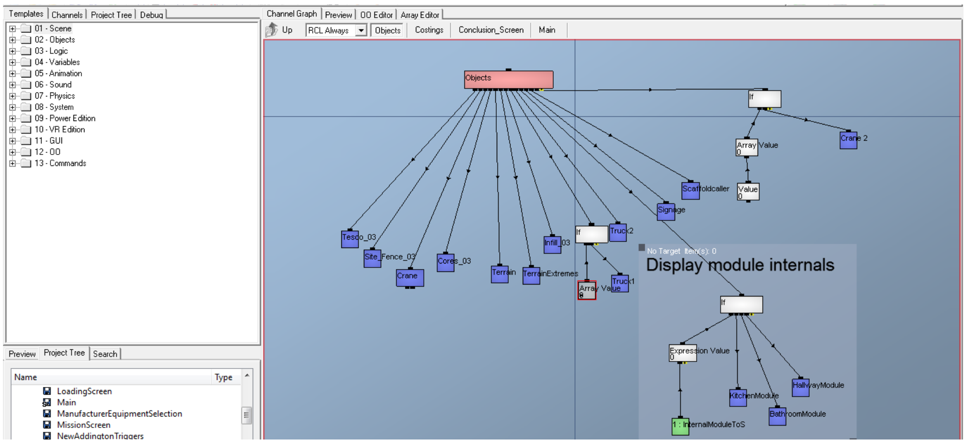


FIG 8: Static Objects Connected to the Interface.

In terms of assembling dynamic objects, the system relies on project schedule imported from MySQL database (Fig. 5), assembly sequence, and project time. Based on the given sequence, the system checks for assembly permission for each module and if the project time coincides with the time allocated to any module, programme runs the related animations in order to deliver and assemble that module. However, at some points some random interruptions occur in project sequence, so the implementation process continues only after the learner sends right emails to right personnel. In this case, a Trigger Channel reinitiates the performance of system subject to delivery of emails to the database. Delays in making the right decisions would result in an increased project cost and completion time.

5. CONCLUSION

This paper presented a cloud-based VR Construction Site Simulator to provide trainees with simulation experience of the construction site of the future. The developed simulator offers a risk free environment where trainees can evaluate how decisions they make would affect their business. This includes but is not limited to analysing issues occurred on the construction site such as: design concerns, process concerns, logistics concerns, and supply chain issues etc.

This paper explained the adapted Unified Software Development Process of specifying the simulator, which employed iterative phases of Elaboration, Construction and Transition. In the first stage of the prototype development lifecycle, the project established the requirements and priorities of the project and represented them in an ontological structure. This can contribute to the body of knowledge in AEC area by identifying the causal drivers and influences associated with successful decision-making design in non-collocated teams. The findings from this study are a stepping-stone for developing new insight and understanding into collaborative environments, particularly though game interfaces. This is the first of its kind to measure and gauge actor involvement, positioning, and organisational behaviour (within an AEC setting), along with social constructs – the nuances of which are likely to contribute to the wider understanding of Management Theory (organisational setting). However, further study is proposed in order to explore undiscovered impacts of the developed simulator on site-level critical decision making by different professions (roles/levels). This may for example include pedagogy and learning traits (Goulding & Syed-Khuzzan, 2014). Similarly, the Charrette Test Methodology (Clayton et al., 1998) could be useful in testing and validating the actual functionality of this system when used in real-life projects.

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