Interactive Generation of 'Multi-Level of Detail' 4D CAD Simulations

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Abstract

Four Dimensional (4D) CAD is becoming a more widely recognised tool to assist in the construction planning process. The ability to link a 3D graphical model with a project schedule provides the ability to visualise the construction process and can further be used to analyse construction operations prior to work commencing on site. Over the last decade, much research has been undertaken in the field of 4D CAD simulations, however a key aspect that still requires attention is the inclusion of the suitable level of detail for the simulation to be realistic. Within existing software tools, the temporal resolution (i.e. the time period between state changes in the 3D model) is fixed. However, construction operations are highly dynamic and as such the temporal resolution very often would require changing for various operations within the same project. A prototype software toolkit is presented that allows the 4D simulation to be generated semi automatically from a real time VR model. 'Dynamic geometry algorithms' are implemented to automatically divide the product 3D geometry based on predefined strategies and during this process multiple temporal resolutions can be included in the underlying 4D simulation database. When the simulation is viewed in a real time VR based 4D engine, the user can select the appropriate temporal level of detail to view operations to provide a more realistic construction process simulation.

Keywords

Construction Planning, 4D, Level of Detail, Resolution, VR Simulation

1. INTRODUCTION

Although 4D CAD in the construction industry has been developing since 1987 (Fischer and Kam, 2001), the interest in this area has grown rapidly in recent years. Barrett (2000) perceived this technological development as having the potential to provide an improved relationship between construction designers and constructors. 4D CAD was seen as a natural progression to 3D CAD models, as it adds a further dimension (time) (Phair, 2000). It provides the ability to represent construction plans graphically (Williams, 1996), by adding the temporal dimension to 3D CAD models, i.e. linking a 3D graphical model to a construction schedule through a third party application (Collier and Fischer, 1996; McKinney et al., 1996). In addition, Kutsson (2000) viewed 4D simulation as a 3D interface to the construction process model, whilst Koo and Fischer (2000) highlighted its ability to visualise progress of the construction phase, by linking units of work to the work tasks on the construction schedule.

Work carried out by Coles and Reinschmidt (1994) demonstrated that creating a 3D model over time assisted in the planning process, whilst Webb (2000) envisaged that the use of 4D simulations could assist in halving the waste costs associated with a construction project. The use of 4D technology has the potential to present ideas to clients in order to promote collaborative working (Fischer, 2001; Kahkonen and Leinonen, 2000), and to assist in the problems associated with site logistics and site layout (Chau et al., 2005). Moreover, it can be used to improve site logistics, such as work execution space (Akinci et al., 2003; Heesom 2004; Mallasi, 2005) and to analyse the construction schedule to assess its executability (Koo and Fischer, 2000). Additionally, 4D simulations have proven useful as a medium for the evaluation of alternative construction schedules (Vaugn, 1996). It also facilitated the review of developed schedules in order to determine potential mistakes and create more robust schedules (Songer et al., 2001). Further, this approach has been advocated as a training tool for inexperienced planners (Jaafari, 2001; Clayton et al., 2002). Although the underlying principles of 4D CAD are the same, it has been used for various applications within the construction industry.

4D technology is evolving and becoming more widespread within the construction industry, however, there are still some fundamental issues that need to be resolved in order to produce more realistic simulations. One aspect that requires further investigation is the issue of the level of detail of a 4D model (Heesom and Mahdjoubi, 2004).

This is particularly true when using the simulation for analysing process such as the inclusion of workspace (Akinci et al., 2003). Within any 4D simulation there are two potential levels of detail. The graphical level of detail refers to the amount of geometric data available within the 3D model. The temporal level of detail (or temporal resolution) can refer to the amount of time between specific time frames within the simulation (this could also be linked to the planning horizon of the construction planner).

The graphical level of detail of a simulation is entirely reliant on the detail contained within the preliminary 3D CAD model. Tanyer and Aouad (2005) further exemplified the problem of graphical level of detail within 4D simulations. This study highlighted that if a 3D model carried little graphical detail some tasks were overlooked in the simulation, whilst if the 3D model had too much detail the project planner was not interested in many aspects. The work suggested that the level of graphical detail should be concluded prior to the simulation being produced.

The temporal level of detail relates to the interval of time that is shown between state changes in the 3D model and how often the 3D model is updated to show the progress of construction operations. The construction process is highly dynamic and as such the state of the construction 'product' can change on an hourly basis. Conversely, some construction operations are slow to evolve and in this case it may take a week for any significant state change to occur in relation to the 3D model.

Work undertaken by Akbas and Fischer (2002) suggested the implementation of zones to generate more dynamic 4D simulations, and these zones could be generated at various levels of detail. However this process was manual and was required to be set during the generation of the simulation. Preliminary studies undertaken have highlighted that specific construction operations require visualisation at different intervals in order to provide meaningful results. For example, piling operations change on an hourly basis as excavation, reinforcement placing, concrete pour and capping can occur within one hour. Conversely, traditional brick wall construction can take days for a significant state change to occur (Heesom, 2004).

Many current 4D methodologies do not take into account the varying productivity factors involved in the dynamic construction of building products and as such very often 4D simulations are run using a single planning interval throughout the duration of the project with no methodology for automatically varying the temporal level of detail as the specific project tasks dictate.

2. DYNAMIC 4D MODELLING

When developing 4D models, one aspect explicitly linked to the temporal level of detail (or temporal resolution) of the simulation is the ability to group construction product(s) that can then be linked to construction tasks.

When analysing the construction process using 4D models, the development of more dynamic 4D simulations is a factor vitally important to obtaining more credible results (Heesom and Mahdjoubi, 2003). However, this area has received relatively little attention. Dawood et al., (2002) have approached the problems of more dynamic simulations through the manual grouping of objects in the initial 3D product model. Using this system, the construction planner can group entities within the CAD model and link the groups to specific tasks on the construction schedule. A similar technique is employed by some commercially available 4D CAD packages (Bentley, 2003; Common Point Technologies, 2005).

Akbas and Fischer (1999) proposed an alternative method to manual grouping, describing two methods of developing more dynamic 4D simulations, Elaboration and Aggregation. Using elaboration, a mechanism is used to decompose a single component into subcomponents (according to zones) and associated activity into sub activities (Akbas and Fischer, 2002). These zones can be generated at various levels of detail to assist in a more comprehensive view of the schedule (Fischer et al., 2000). Various aspects, including the shape of the construction zone, affect the productivity rates used during the development of the dynamic aspect of the geometry axes (Akbas et al., 2001). Using the aggregation method, single components in the product model are combined to form new components, a similar approach to that of Dawood et al., (2002).

Mallasi and Dawood (2003) proposed an improvement on the 'grouping' or 'aggregation' methods described above. Using a genetic algorithm, execution patterns are specified, allowing the planner to identify various constraints such as the starting location for the task, associated products and the direction of work. A production rate can be implemented to describe the amount of work undertaken on the product group for each week of the duration, and based on this, the system automatically produces sub-groups of objects, which can be viewed in the 4D CAD environment.

Both the elaboration (decomposition) and the aggregation (grouping) methodologies provide the ability to produce a more dynamic 4D simulation. However, currently there is no scope to use both techniques on single product groups. The elaboration method can be used only on a single element.

The ability to group (or decompose) building products in a 3D model is a key-factor in the implementation of realistic multiple level of detail. The evolution of the geometry, mirroring the evolution of a building product, will need to be shown based on the temporal resolution of a construction task.

3. PROPOSED APPROACH

In order to fully incorporate the level of detail into simulation environment, a suite of tools are proposed to allow the generation of dynamic 4D models exhibiting various temporal resolutions. The following sections highlight the salient requirements for a toolkit of this nature.

The use of a formalised Work Breakdown Structures (WBS) is increasing within the domain of construction planning (Winch, 2002). However, the adoption of a more formalised Product Breakdown Structure (PBS) is not yet common. Various initiatives are available to provide a formalised PBS. However, these are rarely implemented within the industry context. Techniques are currently available to allow the building product model to be formalised according to a specific classification. For example, the Uniclass standard allows both products and processes to be formalised using a generic alphanumeric code. The provision of a more structured PBS using the Uniclass system will assist in the effective decomposition of tasks during the development of a 4D CAD simulation. This will allow products and processes to be linked through use of the same structured classification code.

Currently, 4D CAD simulations are static, as they illustrate completed building products for the entire duration of the associated task. Some initiatives are attempting to resolve this fundamental issue, using either a technique to group individual elements or decomposing a single building element based on associated task duration. A more rigorous approach would be the combination of these two methodologies, allowing product groups within the PBS to be both decomposed and grouped into dynamic elements (Figure 1).

Whilst it is acknowledged that full automation often removes control from the planner (for example use of expert systems to generate construction schedules), the semi-automation of certain routines can provide increased productivity. When generating 4D CAD simulations, the manual linking of product to process is an arduous task. However, the semi-automated linking of the PBS to the WBS would allow the linking of products and processes to be carried out automatically as the schedule is being generated, which allows the removal of the intermediary 'linking' stage. The integration of this principle, combined with the concept of allowing the construction planner to generate tasks whilst viewing a 3D computer model of the completed building, would provide an improved integrated approach to semi automatically connect the product and process.

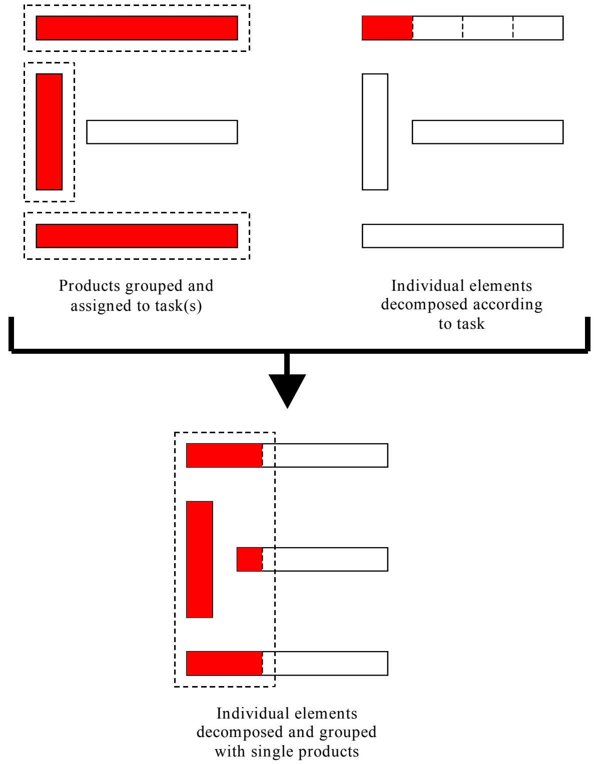

Figure 1: Proposed dynamic geometry technique

Real time simulation methodologies provide the ability to fully interrogate a 3D model, by viewing it from any location and interacting with the objects. The use of real time techniques within a 4D CAD simulation, allows the planner to view all aspects of the model in real time. This provides an increased comprehension of the construction schedule, by allowing the evolving building products to be viewed from any location. This approach would also provide the ability to interact with objects and retrieve specific information.

There are two levels of detail used during the creation of a 4D CAD simulation. Firstly, the graphical representation of the building products is subject to a level of detail. When using 4D CAD for analysing the construction process, Heesom and Mahdjoubi (2003) emphasised that a low level of graphical detail is adequate. In order to analyse the process of construction, simplistic graphical representations of building products are adequate to convey the relationship of the 3D objects. It is suggested that full photo-realism would not provide beneficial information. Alternatively, the time lapse between process visualisation is a further level of detail within the 4D CAD simulation, which requires consideration.

4. SYSTEM DEVELOPMENT

The implementation of the software tools to generate dynamic multi-temporal resolution 4D models is the focus of this paper. In order to achieve the aim of developing a toolkit capable of this, a modular software development framework was adopted. Based on the key requirements specified in section 3, the software toolkit centred on a multi-document-interface (MDI) methodology with specific modules interacting and performing key tasks in the generation of a 4D construction simulation.

The system moves away from the manual methodology of linking tasks to building products (as seen in commercial systems). Additionally, the system does not propose the completely automated method of linkage as seen in work undertaken. The toolkit aims to provide a 'planner centric' environment to allow the construction planner to retain control over the linking of tasks, the specification of the level of detail required for specific operations whilst helping to semi-automate the linking and 4D development process. The key processes of the proposed toolkit are detailed in Figure 2 using the IDEF0 modelling methodology.

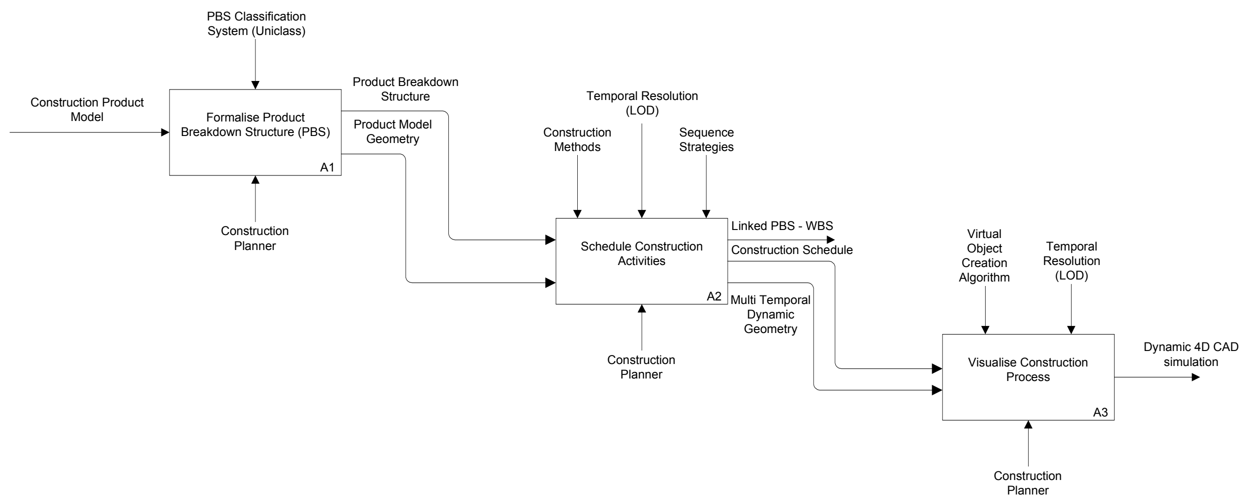

Figure 2: Outline system development methodology

4.1 Data management structure

Prior to any process being undertaken, the central core of the proposed system will require the management of complex inter-related data. This will include temporal data for the construction processes and the storage of geometric related properties for each building product. It is proposed that the data management will be undertaken through the implementation of a Relational Database Management System (RDBMS) allowing the storage and accessing of data for all processes (and modules) undertaken by the system.

This relational structure provides for individual entities to be stored within 2D tables whilst various relationships between tables can be derived (Anumba, 1996). Each of the aspects required to formulate a dynamic multi resolution analysed construction process, will require access to the data. Additionally, each procedure will necessitate the ability to read and write information to the data management module.

By definition, the relationship between construction products and construction tasks can be classified as a Many-to-Many (M:N) relationship. According to Carter (2000), this form of relationship within a RDBMS is unwise and can lead to duplication of data.

It is therefore prudent to introduce a further entity to establish two One-to-Many relationships (1:N). The One-to-Many relationship within the proposed approach will introduce the Uniclass code of building products as a distinct entity. In this regard, many construction tasks can be related to a single Uniclass product code and a single Uniclass product code can be related to many building product elements (Figure 3).

The Uniclass product code shall be the Primary key in a specific table, whilst the code also exists as a foreign key in both the construction task and the building product tables. The proposed schema for the RDBMS is illustrated in Figure 4. The table holding information regarding the Uniclass codes of building products can also be used to store information pertaining to the specific building levels, which exist within the building.

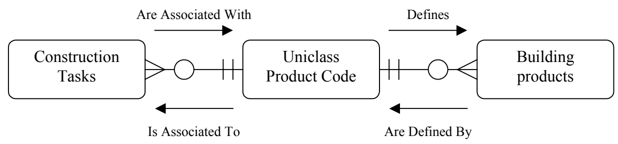

Figure 3: Product-process relationship using two 1:N relationships

The data management of both the temporal and spatial information plays a key role in the integration of the developed toolkits. Each of the processes and concepts highlighted in Figure 2 has been developed into discreet software modules (depicted in Figure 5) and interact with the RDBMS which is implemented in Microsoft Access. The specific software modules utilise the Data Access Object (DAO) protocol to exchange information with the MS Access RDBMS.

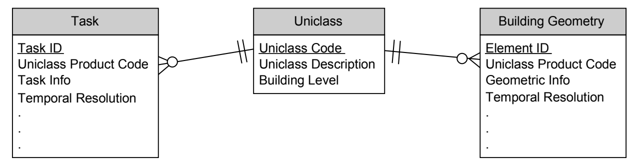

Figure 4: System Database Schema

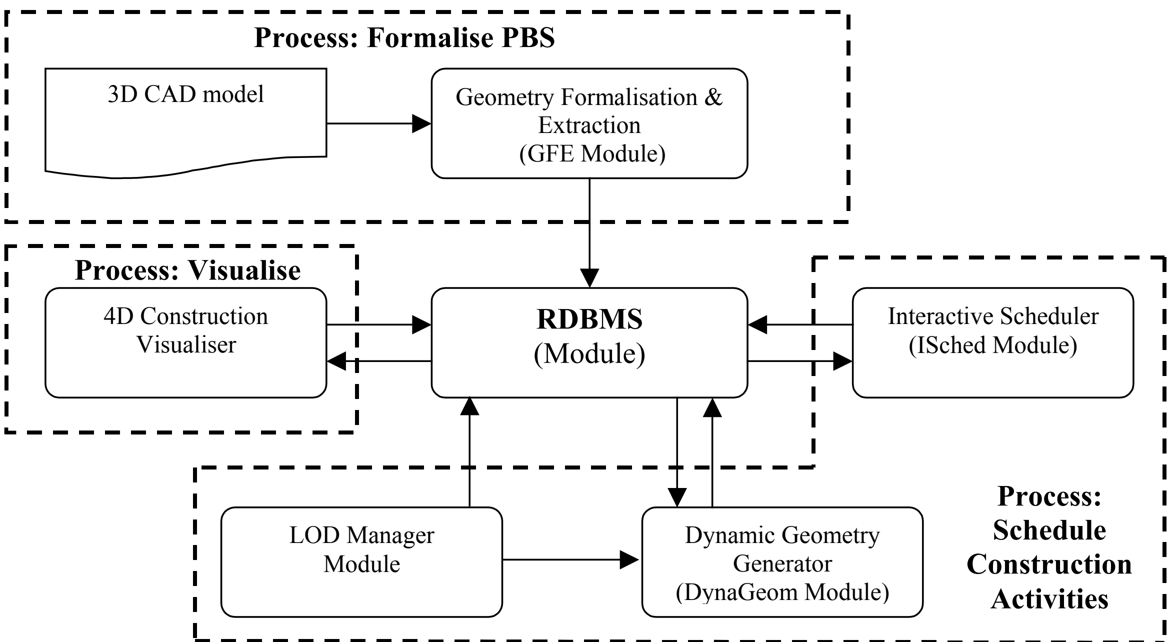

Figure 5: Outline System Architecture

5. FORMALISING THE PRODUCT MODEL

The initial 3D product model forms the main input to the proposed system. Currently, commercial CAD packages, for example AutoCAD, are increasingly utilising 3D modelling methodologies with the inclusion of parametric technology. These 3D models however, are rarely formalised into a standardised product breakdown structure according to a classification system.

This study advocates the classification of the product breakdown structure model through utilisation of the Unified Classification System for the Construction Industry (Uniclass), Crawford et al. (1997). This UK based standard will allow all elements within the product model to be classified according to the specific code, and will also serve as a technique for allowing tasks associated with building products to be linked. The implementation of the Uniclass standard into existing drawing practice requires little culture change in current CAD modelling techniques and so allows rapid infusion into the industry. Generally, layers within a CAD model are used to develop an initial product breakdown structure during the design process. However, it is often the case that the layering convention used is not compliant with a specific method and is often based on individual company standards (Davies, 2002). This technique will enable the products and processes used in the construction project to be classified using a generic standard. The classified product model provides input into the 3D task scheduler where each of the product groups is decomposed into a breakdown of tasks or processes. Once formalised, the geometry from the product model can be extracted into a Relational Database Management System (RDBMS) for further use.

The 3D formalisation module of the system allows the planner to formalise an existing 3D CAD model using the Uniclass classification system. The module initially reads an AutoCAD drawing file (*.dwg) as input. The layers in this file are then read into the module and displayed to allow manipulation. This tool allows the planner to formalise the layering convention used, without having to access the drawing file directly within the CAD software environment (Figure 6).

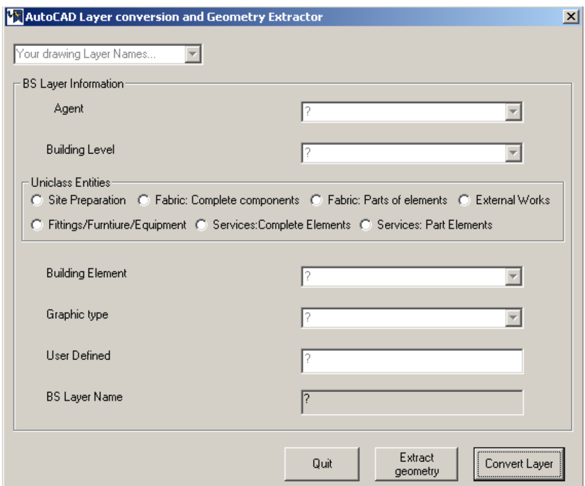

Figure 6: Product Model Formalisation Module

Once all required layers (or products) are converted to be compliant with the Uniclass structure, the geometric properties of all building elements contained on these layers can be extracted into the database. The extraction routine uses the 'Bounding Box' principle to determine the simplified geometric attributes of each element within the CAD model.

6. SCHEDULE CONSTRUCTION ACTIVITIES

Traditionally, experienced personnel mentally decompose the building products depicted on construction drawings into constituent elements and generate a construction schedule. Once a complete schedule of tasks is generated, it can be linked to the 3D product model for the creation of a 4D CAD simulation. A novel methodology is presented eliminating this intermediary 'linking' process whilst assisting the planner in having a greater comprehension of the tasks required to construct the completed facility.

This methodology offers a novel approach to support the development of construction schedules, and overcomes the problem of manual linking of PBS to WBS. The use of an interactive scheduling tool will allow the planner to view a 3D model of the final product and select specific groups within the PBS. Once selected in the 3D model, the building products can be highlighted and specific tasks developed. Through using this approach, the planner will be automatically undertaking the process of linking product to work process.

With the 3D VR model, the planner will have the capability to select different groups existing within the formalised product breakdown structure, according to their Uniclass classification. Task(s) can then be created as required to complete the construction of these products. The temporal scheduling engine proposed in this study is the Microsoft Project software tool. This package provides a high level of functional ability (Heesom and Mahdjoubi, 2002) and is also popular within the industry (Aouad et al., 2001). Whilst a key issue is to semi automate the PBS – WBS linking, it is also essential to ensure that the construction planner is at the centre of task creation and logic. This methodology serves as a support tool allowing greater comprehension of the completed product, whilst also allowing full control over the construction scheduling process.

The Interactive Scheduler (ISched) module (Figure 7), allows the planner to select product groups from the formalised product breakdown structure and allocate the task(s) required to complete the construction products. This module has two aims. Firstly it assists in alleviating the time consuming task of linking product to process in order to carry out a 4D simulation. Secondly, the module assists the planner in producing a more rigorous construction schedule through the visualisation of the completed facility during the scheduling operation.

Using the relationship established between the Uniclass coding for each element group in the building and the geometry information extracted from the CAD model, the ISched module generates 3D virtual reality objects for each entity within the formalised product group. The geometric properties of each element on every building level are extracted from the DBMS and VRML coding is generated on the fly to describe these objects

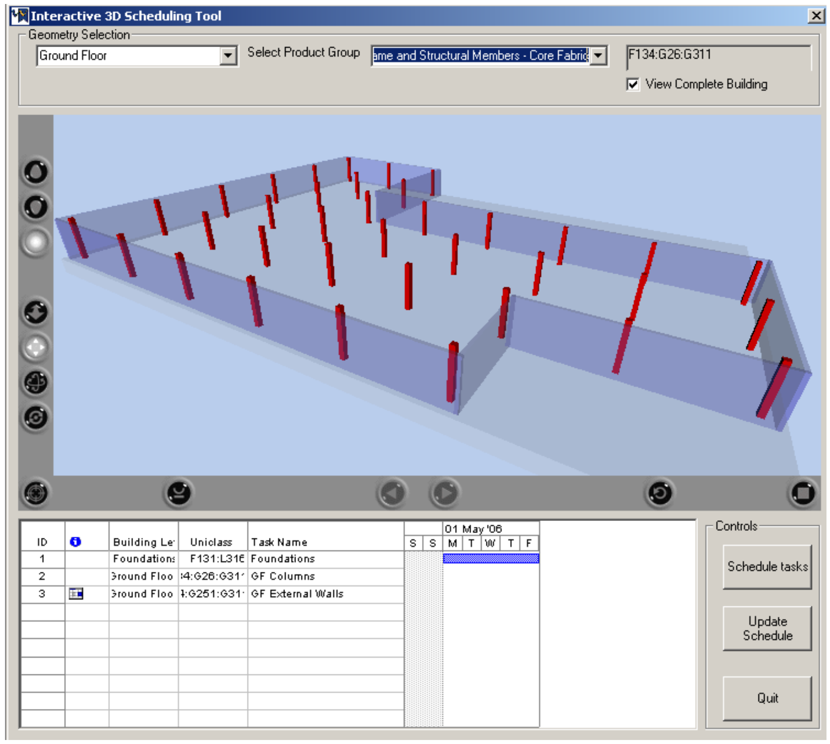

Figure 7: Interactive Scheduling of Construction Activities

6.1 Dynamic Geometry Generation

The decomposition and aggregation theory, proposed by Akbas and Fischer (2002), relies on a complex algorithm to automate the creation of dynamic geometry through productivity factors. Work undertaken by Mallasi and Dawood (2003) present the use of advanced methodologies to group individual objects and assign groups of objects to tasks.

The approach proposed in this study utilises a novel methodology involving decomposition and product grouping. Through the formalisation of the product breakdown structure, allocating work tasks to groups of classified product elements creates the schedule. This approach will use both automated algorithms and manual driven techniques to decompose the individual product groups associated with tasks into individual dynamic geometric elements, allocated to specific duration units of the construction schedule. The use of linear construction strategies, based on linear work patterns such as those discussed by Riley (1994), is adopted. Manual methods of decomposing product groups will allow more bespoke (or random) strategies of construction to be applied.

The dynamic geometry generator module (DynaGeom) (Figure 9) provides the construction planner with the ability to further decompose the product breakdown structure, according to the duration of the task(s) associated with individual product groups.

The module uses a developed Dynamic Geometry Algorithm (DGA) to semi automatically decompose groups of building products into sub-elements, highlighting building products that are either completed, in progress or not started. The DGA uses the concept of regions or zones to divide the construction site according to the duration required to construct a set of building products. The DGA is divided into 2 stages, the first stage calculates the construction regions based on linear strategies, whilst the second stage decomposes products within the calculated regions to determine physical geometry (Figure 8). This geometry is then stored in the dynamic geometry store within the RDBMS.

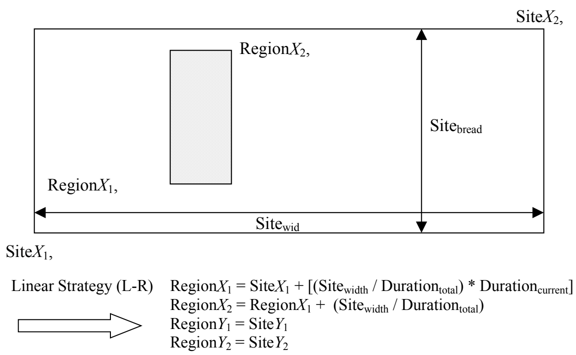

Figure 8a: Calculation of linear strategy regions

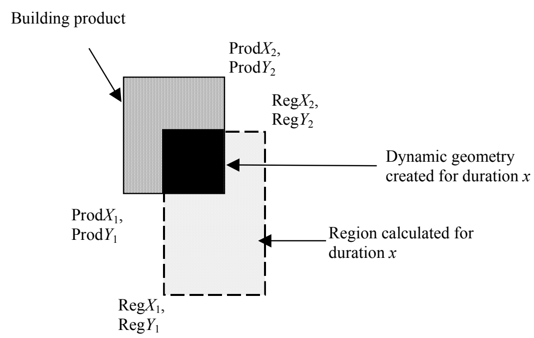

Figure 8b: Determination of building element within DGA region

6.2 Level of Detail Management

During the decomposition of the product geometry within the 'DynaGeom' module, the construction planner also has the ability to review the resolution of the planning horizon to be used during the 4D simulation. This resolution has an impact on the regions developed for the calculation of the dynamic geometry, i.e. how many subdivisions there are depend on the LOD selected (for example 1 week unit = 5 day units). For each product group selected within the simulation the options of daily, weekly or monthly or bi-monthly are available and the planner can select the appropriate resolution for the construction operations (Figure 9).

Two techniques are employed to assist the planner in developing the appropriate level of detail for the 4D simulation. The first technique allows the planner to explicitly specify the temporal resolution of the process and product under construction. Once selected the total product geometry associated with the task(s) is decomposed into the required no of units to match the LOD specified.

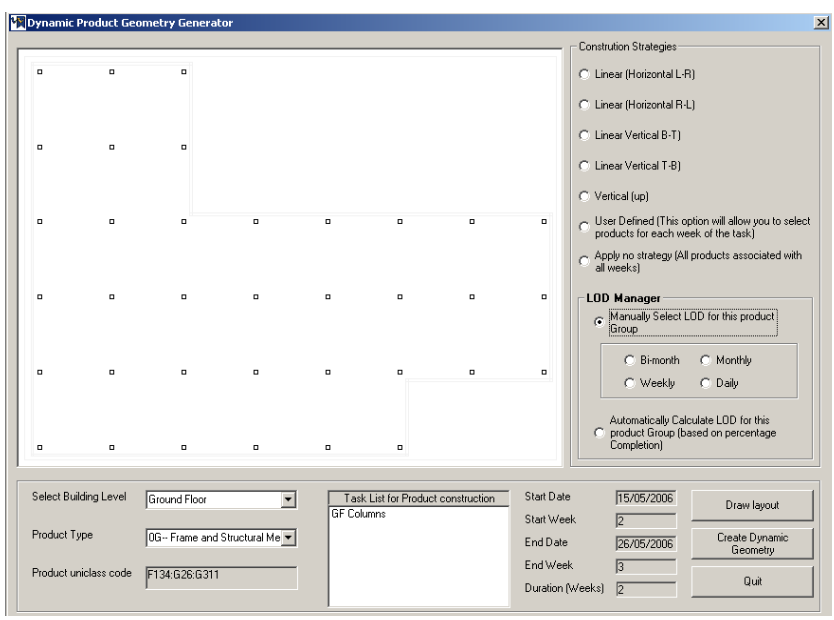

Figure 9: Developing Dynamic Geometry and LOD

The planner is also presented with the option of defaulting to specifying the duration of the process in weeks and then providing information on what percentage of work will be completed during each week. Using a simplistic rule based algorithm, the system will calculate the temporal resolution required for the task(s) based on anticipated completions specified by the user. These rules are based on an assumption that completion of more than 50% in one specified time frame will require an increase in the resolution in order to provide a more detailed view of the construction process. For example, if the duration of the task(s) is 3 weeks and during the first week 60 % of the task and allocated product will be complete, the system will default to providing a daily level of detail for the entire task duration such that sufficient detail is included to highlight the dynamic nature of the task during the first week of construction.

Based on the level of detail selected for the task and product group, the DGA sub-divides the building product geometry into regular segments and stores the completed and in progress geometry within the dynamic geometry store in the RDBMS.

7. VISUALISE CONSTRUCTION PROCESS

Khosrowshahi and Rad (2000) advocated the use of real time simulation technologies for 4D construction process simulations, adopting the Virtual Reality Modelling Language (VRML) to generate the visual display. This technique was also adopted by other initiatives in the field of construction visualisation, including Kahkonen and Leinonen (2001), Lipman and Reed (2000), Campbell (2000) and Aouad et al., (2000). These efforts demonstrated that a 4D CAD visualisation could provide the planner with a greater comprehension of the construction process.

The 4D Visualiser module provides the ability to view the construction process in four dimensions (4D). The 4D Visualiser module of the system implements VRML to display the 4D simulation model of the construction site. The module utilises the Cortona Control Software Development Kit and the associated ActiveX component developed by Parallel Graphics to allow the dynamic generation and manipulation of 3D objects in the virtual environment (Figure 10).

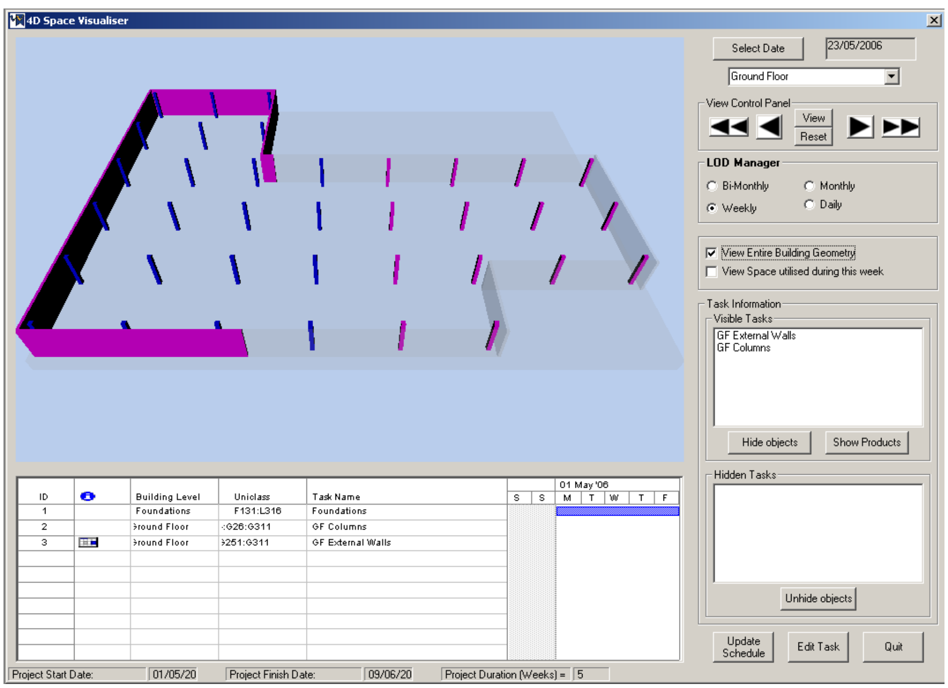

Figure 10: Multi LOD 4D Visualiser Module

The 4D Visualiser module also detects and displays all tasks being undertaken at the date specified. By querying the task list in the RDBMS, the Visualiser module provides the user with a recommendation of what temporal resolution is best to view the specific date and subsequent times during the schedule duration.

The 4D Visualiser module also provides the ability for the planner / user to dynamically update construction tasks, update construction strategies (along with originally specified temporal resolutions) and recompile the 4D simulation in real time. The user can select a specific Task(s) from the list and update the task dates and subsequently amend the strategy. These calculations are done in real time and so the 3D model in updated to show the amendments instantaneously.

7.1 Dynamic management of LOD

Within the 4D Visualiser module, the system provides an 'intelligent' technique to allowing the ability to manage the level of detail at which the simulation is viewed based on the dynamic geometry developed in the previous process.

Each task and associated Uniclass grouping stores a code that describes the temporal resolution of the tasks. The 4D Visualiser module reviews all tasks in progress during the specified date by the planner within the 4D Visualiser and assesses the most appropriate level of detail for viewing the construction process at the time specified. The system reviews all tasks and product groups and allows the planner to review a list of tasks and level of details specified.

The module provides a percentage breakdown review of the various temporal resolutions that exist on the date specified by the planner. The review process within this tool can be overridden, allowing the simulation to run in the more 'traditional' manner. This allows selection of a default time frame and running the simulation using this value. The simulation will ignore level of detail information for tasks and products in a higher (or lower) resolution than that specified and will show the building product development according to the temporal unit specified. In order to run in this mode, the system makes assumptions that 1 week unit = 5 day units and 1 month unit = 4 week units.

The Visualiser module, queries the task table in the database and by reviewing the LOD field and produces a recommendation. If over 30% of the tasks in the table have been specified as having a specific LOD requirement (weekly, daily etc...), the Visualiser informs the user and suggests amending the temporal resolution to the most prominent LOD available. When the user selects a resolution option, the Visualiser regenerates the VRML coding for the date specified and displays this. Additionally, the step change for the date using the video control panel adjusts accordingly.

8. CONCLUSIONS AND FURTHER WORK

This paper has presented a novel 4D real time VR based planning system that provides a methodology for semi-automatically generating dynamic 4D simulations at various levels of temporal detail.

The toolkit is currently under testing and validation on projects within the West Midlands region of the UK and is demonstrating potential to provide a more robust method of visualising a realistic picture of the construction process.

Future developments of the software toolkit and temporal resolution methodologies are currently underway and these include underlying techniques that will incorporate productivity factors into the development of the dynamic geometry using this technique. This method is incorporating measurement calculation quantities to calculate completion rates and using these rates and measurement techniques, dynamic geometry is generated using the most appropriate level of detail.

Currently, the geometric algorithms are simplified, however enhancements will allow for highly irregular shapes to be included in the development of dynamic geometry and also allow for irregular, bespoke, construction products to be incorporated within the productivity based dynamic geometry creation described above.

At the current stage of development, the software toolkit allows for the work process to be developed and visualised using monthly, bi-weekly, weekly and daily units of temporal resolution. However, some tasks can change by the hour and as such this unit will be added to the dynamic 4D visualisation. This will allow geometry to be developed and viewed in hourly work units.

The systems and toolkits developed and presented in this paper are also part of a larger study will has developed a novel methodology for space planning on the construction site, allowing planners to specify required workspaces and route paths interactively based on a fully dynamic simulation of the construction process. The concepts described in this paper will provide a more dynamic and realistic method for space planning on the construction site.

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