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THE NEED FOR MULTI-LOD 4D SIMULATIONS IN CONSTRUCTION PROJECTS

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SUMMARY: *The increasing application of BIM processes and technologies has facilitated an increase in the use of 4D (3D+Time) simulations of construction projects. Previous research has acknowledged the benefit of 4D models in the project planning and construction phases enhancing communication between construction teams and avoiding unforeseen conflicts during the build process. The development of BIM has spurred a deeper understanding of the issues surrounding Level of Development, Level of Information (LOI) and Level of Detail (LOD) pertaining to the graphical detail and non-graphical information of the static geometric design model. However, to date there is limited research thoroughly investigating the issue of LOD within 4D applications. This work presents an ongoing study to derive a framework for the development of more dynamic 4D simulations incorporating discrete forms of LOD. Level of graphical detail (LOD_g) corresponds to the graphical detail of the model geometry and also the 'granularity' of the geometry required for dynamic 4D production, whilst the temporal level of detail (LOD_{ti}) relates to time period required between state changes in the model during the simulation. In order to support the development of the framework, an industry-based survey was conducted to assess the application of 4D, subsequent issues and use cases around levels of graphical and temporal details to improve dynamic 4D simulations. The work concludes with the development of a framework and schematic to support the specification of the LOD of a 4D simulation (LOD_{4d}) throughout the various phases of a construction project.*

KEYWORDS: *4D, Level of Detail (LOD), BIM, Simulation*

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1. INTRODUCTION

Building Information Modelling is now a crucial part of the construction process, where the creation of a 3D geometric model starts early in the development cycle (Mordue *et al*., 2016). The level of development (LODt) defines the precision of the 3D elements and the quantity of non-graphical information contained in each element accordingly as the model evolves (Bedrick, 2013). The graphical Level of Detail (LOD) within a BIM is defined and based on individual elements, as well as the development of the elements all the way through the project from the conceptual design to the highest level of the representation (as-built). Whilst BIM has allowed a greater flow of information throughout the lifecycle of a construction project it has not completely resolved this issue of lack of sufficient design and construction information at the planning stage. Winch *et al*. (1998) noted that the lack of information at this stage was a key problem affecting effective construction planning. The issue of LODt has received attention from BIM researchers and practitioners including The American Institution of Architects (AIA) who developed principles to assist communication during the construction project. AIA E202 is a document providing guiding principles about the models, indicating the relationship of the level of development with the proposed use of the model at every stage of the project (Kensek, 2014). In the UK, the PAS1192 documents (BSI, 2013) and the NBS Toolkit (NBS, 2015) provide guidelines and templates for the LOD requirements at various stages of the design and construction process.

Construction planning is a critical element of a project ensuring that tasks are completed in a logical and timely manner. At the present time the development of the schedule is undertaken by the construction planner who has the expert knowledge to derive logic between relationships and also the ability to breakdown tasks into sub processes as the construction sequence progresses to provide a greater level of information to the team (Sigalov and Konig, 2017). Winch (2010) further discussed the evolution and increasing detail of tasks through the Work Breakdown Structure (WBS) at key stages of a project. Noting that as the WBS increased in granularity during the design, planning and construction phases, so can the Product Breakdown Structure (PBS), providing the opportunity for these to be linked together to provide a 4D simulation. The level of detail of a construction schedule is defined by various authors who provide underlying nuances, essentially follow the same philosophy that detail increases as the project design and construction continues. Jelen's schedule levels (Humphreys, 1991) progress from Level 0 to Level X moving from whole project level to individual task specific sub schedules, but noting that there is no universal specified number of levels. Various other protocols exist to support the definition of the level of detail of the construction schedule including the use of numeric levels and descriptive levels of detail (AACEI, 2010).

Trani *et al*. (2015) highlighted that the Level of Graphical Detail of a 3D (BIM) model varies during the design and construction of a project, and these can be used for various planning activities during each stage. Additionally, levels of detail must correspond to the industry needs' and the estimated usage of the model at different phases of the construction project (Boton *et al*., 2015a), deriving a higher or lower degree of realism for the 4D simulation as the need arises. Faloughi (2017) identifies that the production of 4D is not a one off event, and different simulations will be generated at various stages of the project lifecycle. Each of these may require a differing LOD. This specific area of research to understand the alignment of schedule, 3D and 4D Level of Detail has attracted a limited amount of attention and is subsequently the focus of this study.

2. 4D BIM AND LEVEL OF DETAIL

Since the late 1990s, a wide range of research has been undertaken in the field of 4D modelling including the application for collaboration, space planning and the use for health and safety (McKinney and Fischer, 1998; Aouad *et al*., 2012). The use of 4D adoption is increasing within the construction sector with upper management beginning to see the potential benefits of using it as a viable planning tool (Gledson, 2015). Issues of LOD around the 3D geometric (BIM) model during design and construction have received attention both from practitioners and researchers. However, even with a great deal of attention, Grytting *et al*. (2017) noted that there were still issues to be resolved as a number of models were delivered with a higher or lower LOD than necessary leading to change orders. Whilst the LOD protocols for the design model provides guidance to those interacting with the 3D geometric aspect of the final design, there has been little work presented to fully understand and define the specific level of graphical and temporal detail required for 4D simulations throughout the construction process. As such the LOD for 4D is still not well defined nor is the way to develop a simulation with a specific approach to LOD management (Guevremont and Hammad, 2018).

Both the graphical and temporal detail of a 4D simulation must be such that it can facilitate effective managerial decisions and thus construction processes during the project (Guevremont and Hammad, 2018). Furthermore in order for a 4D simulation to remain useful throughout the duration of a construction project, it must be continually used, evaluated and refined as the project progresses (Umar *et al*., 2015). This continued maintenance of the 4D simulation is subsequently seen as a limitation to the implementation of 4D during the construction process (Romigh *et al*., 2017). The use of 4D changes throughout a project, as does the use of the entire BIM dataset. Furthermore, the view of the BIM dataset can vary depending on the viewer. To resolve this phenomenon, Tolmer *et al*. (2017) propose a Level of Abstraction (LOA), which identifies the relevant objects that need to be considered for the specific use of the BIM. This concept may be something that could be applied to 4D to propose the specific LOD for use cases.

Trebbe *et al*. (2015) highlight how 4D BIM can be used to understand complex interconnections between different stages of construction work in any project. The individual 3D elements within the 4D simulation allow project stakeholders to view the what, where and often how of the construction process from design, procurement and construction schedules. Aouad *et al*. (2012) postulated that more dynamic 4D simulations were required in order to achieve more reliable outcomes, when used in the planning process. Boton *et al*. (2015b) also noted that levels of detail of the graphical models used during any 4D simulation must correspond to the industry needs' and the usage of the simulation at different phases of the construction project. Faloughi (2017) supported this notion whilst also proposing questions such as whether the BIM models are developed enough to match the level of detail of the schedule or are too detailed for the purpose of the 4D simulation. Building on these issues, it has also been acknowledged that any specification of 4D LOD should manage both the graphical level of detail and the temporal level of information, in order to deliver realistic and more reliable 4D simulations (Tolmer *et al*., 2015). However, little has been undertaken to formalize these issues.

According to Aouad (2012), in order to assist more dynamic 4D, the 3D model creators need to have approached the geometric composition in such as way that it can support the 4D activities and 3D models have to be organized into work components to match the level of detail in the schedule. However, in many cases the initial design model is often not created with the intention for it to be used for planning or control purposes and often leads to the contractor generating a new model for the purpose of developing a 4D simulation. It is at this point that they may consider the LOD required to produce a viable 4D model, subsequently updating the representation of geometric objects (Lui and Li, 2013). As part of this process the granularity of the geometry of the 4D simulation can require either the subdivision of elements or the aggregation of elements to create the geometric portion of a '4D Object'. As early as 2008, Tulke *et al*. (2008) proposed an algorithm based approach to split geometric objects within an IFC file into portions away from the BIM/CAD authoring tool for the creation of more dynamic representations of construction within the 4D software environment. This is now a more commonplace capability in some commercial tools, as is the ability to combine individual elements to create an aggregated group for linking. This variable approach of linking objects provides the ability to better satisfy any 4D LOD requirements (Guevremont and Hammad, 2018). However, there is still an explicit link between the LOD of the BIM geometry and the requirements of the 4D LOD. For example, to facilitate the visualization of a high schedule LOD, a highly detailed geometric model may be required. A typical example would be a 4D showing the installation of cable trays where installation of individual hangers was to be shown. These geometric objects would need to be modelled in the BIM to be available to inclusion in the 4D simulation.

Boton *et al*. (2015b) presented a case study of the development of 4D models at different stages of the design and construction process. However, the development of the Level of Detail within this project was mainly focused on the graphical detail of the design model. Models were created in accordance with the AIA LOD 100-600 series using a range of software tools and then 4D simulations were created. The work did highlight the changes required for the resolution of the plan at each stage and this was appropriate for the detail of the graphical model, also noting that LOD required for the construction phase is higher than the LOD needed in the pre-construction phase (Kriphal and Grilo, 2012). On the other hand, it did not resolve the critical question of decomposition of construction product elements for the generation of more dynamic 4D models and whether this is also required to change to meet the needs of project planning through the various phases of the lifecycle of the design and construction. The study did conclude that a single graphical LOD is not adequate during the construction phase and that different levels of development were needed for visualization and coordination, depending on the 4D model purpose and the specific construction problems that occurred during construction and modelling processes. This view is supported by McGeorge and Zou (2013) who note the understanding of complex models could be aided by the technique of model decomposition that subdivides models into smaller significant sub-models in order of their conception.

It is apparent that in 4D models, LOD specification should manage graphical levels of detail and the temporal level of information in order to deliver realistic and more reliable 4D simulations (Tolmer *et al*., 2015). This is something that was highlighted by Guevremont and Hammad (2018) where two 4D simulations were implemented on a case study project. The low LOD was based on low schedule detail and the higher includes more detailed schedules and more detailed geometric breakdowns. A medium LOD could also be used for workspace allocation. The work also notes the important issues of the time step used in the 4D simulation and this is based on data available in the schedule LOD and the ability to change between the low and high level of detail as required. This becomes a critical issue for 4D simulations moving forward as the ability to step between multiple LODs' within the same simulation session will provide a more comprehensive usability.

The absence of an approach to define and specify the level of detail in 4D simulations for effective evaluation of the construction process was highlighted by Heesom and Mahdjoubi (2003). They indicated that developing more dynamic 4D simulations would provide more accurate and more realistic outcomes (Heesom, 2006). In order to provide a more dynamic 4D simulation, the Level of Detail of the 4D simulation (herein termed LOD_{4d}) must manage both the graphical level of detail (herein termed LOD_g) and the temporal level of information (herein termed LOD_{ti}). The LOD_g is key to providing the end user with enough graphical information of the element due to be constructed. As an example, Han and Golparvar-Fard (2015) suggest that the lack of detail in the 3D BIM used during the pre-construction planning phase is not sufficient enough for tracking the progress on individual element bases but can provide an overview of the process. In addition to the detail of the graphical element, the LOD_g also needs to encompass the granularity of the object(s) being simulated. In this case the granularity is defined as how a single 3D geometric BIM object is potentially sub-divided into constituent parts or aggregated for linking to individual tasks in the 4D simulation, providing a more accurate reflection of the dynamics of construction sequence. The LOD_{ti} within a 4D simulation is a critical factor as this details the time period between state changes in the simulation required for each task i.e. 1 day, 1 week, etc. Further comprehension of the interrelationship between these factors will allow specification for elements within the construction process.

2.1 Existing software tools for 4D BIM

As 4D has evolved and become more prolific through the increasing use of BIM technologies and subsequently 3D digital models, a range of software applications that support 4D modelling have come to market (Table 1). These are part of suite or stand-alone third party applications. The functionality of these tools varies however the core ability is the same whereby 3D components are linked with temporal data through either linking on an individual or group basis. Generally this is undertaken manually, however the functionality of these is evolving by allowing the link to be developed using more automated algorithms using the attribute based data attached to the 3D elements.

As BIM evolves and more 4D tools appear to the market some the functionality of many appear to converge. The basic premise of linking 3D to schedule data is the same throughout all of the above. Many tools have both the ability to import schedule data from most prominent planning tools, including Primavera, Microsoft Project and Powerproject, but are also now providing the ability to generate construction schedules within the 4D software tool. The strengthening of this approach in the future may well see an increasing up take of the 4D paradigm as it will potentially remove the 'linking' stage in the development of 4D. In addition, the ability to import a wider range of 3D geometric formats is becoming a key factor in the tools. Whilst it is acknowledged that most have the ability to import the IFC file format, the ability to import native, proprietary formats appears to be a key area of development. In addition, tools such as Vico have to ability to interact with the BIM Collaboration Format (*.bcf) file type.

With respect to the level of detail capabilities, all of the existing tools have the ability to change the time between state changes of the 4D simulation. These can range from using minutes, hours up to months or also provide the ability to show the progress of the task as a percentage of the time completed. However, it is not possible to have multiple temporal state changes within a single 4D simulation session. For example, in one complete session it is not possible to view progress on a daily basis, then switch to an hourly basis then to weekly basis. This would need to be undertaken as three separate simulations with manual intervention. All of the software tools have the ability to link multiple geometric objects to a single task, or indeed group the objects together and link to a task(s). However, not all of the tools have the ability to subdivide the geometric objects from within the 4D environment. This aspect is critical to developing a level of granularity and a subsequent higher level of detail for the simulation to show greater detail in the process of construction.

Table 1: Current 4D software applications

Company / Tool	Description	Linkage	LOD capabilities	
			Temporal	Graphical
Bentley / ConstructSim Planner	Provides Project and analyse wise schedule simulation. Import 2D and 3D design files difference sources	Importing and connecting schedule information from Microsoft Project, Excel or Primavera. Reviewing interfaces (clashes) and viewing and analysing schedule simulations	Ability to change time between 4D state changes. Not able to change temporal steps / have multiple steps during a simulation.	Able to group objects but not able to subdivide imported geometric objects within the software environment
Autodesk / Navisworks	Supports various numbers of BIM formats and has overall very good visualization capabilities Permits the importation of schedules from a variety of sources	Supports manual and automatic linking to imported schedule data from variety of schedule applications Allows the user to join the items in the model with the tasks and simulate the schedule	Ability to change time between 4D state changes. Not able to change temporal steps / have multiple steps during a simulation.	Able to group objects but not able to subdivide imported geometric objects within the software environment
Innovaya / Visual Simulation	Combines BIM objects with planning activities to complete a 4D construction. Generates simulation of construction process	Increases the project communication, synchronization and logistic scheduling. Links 3D design data in DWG with Microsoft Project or Primavera	Ability to change time between 4D state changes. Not able to change temporal steps / have multiple steps during a simulation.	Able to group objects but not able to subdivide imported geometric objects within the software environment
Synchro Software Ltd. / Synchro PRO ** *(Note that Synchro was acquired by Bentley Systems in June 2018)*	New 4D tool with improved scheduling and project management	Covers risk and resource analyses features and include built in tools to visualize risk, buffering and recourse usage in addition to 4D visualization	Ability to change time between 4D state changes. Not able to change temporal steps / have multiple steps during a simulation.	Able to group objects Ability for geometric objects to be subdivided within the software environment
Elecosoft / Powerproject BIM	4D planning to combine 3D planning and scheduling linking the project plan and model together in one application.	Users are able to import the IFC models in the project plan with full 3D visual impact and to create milestones and baselines to simulate projects.	Ability to change time between 4D state changes. Not able to change temporal steps / have multiple steps during a simulation.	Able to group objects Ability for geometric objects to be subdivided within the software environment
Vico / Schedule Planner and 4D Player	Part of the Vico Office Suite providing the ability to run full simulations of the construction process including 4D and 5D	Uses Line of Balance planning to link to 3D geometric model	Ability to change time between 4D state changes. Not able to change temporal steps / have multiple steps during a simulation.	Able to group objects for link to LOB tasks but not able to subdivide imported geometric objects within the software environment
rib software / iTWO 4.0	5D cloud based enterprise platform that also encompasses the ability to include schedule data for 4D simulation	Import model and develop schedule of activities within the software.	Ability to change time between 4D state changes. Not able to change temporal steps / have multiple steps during a simulation.	N/A
ACCA Software (Italy) / usBIM.gantt	4D BIM project management with project management and scheduling 4D time simulation.	Allows project managers to assign a time-line related property to each components of the BIM model in IFC format in order to see the entire construction process in open formats.	Ability to change time between 4D state changes. Not able to change temporal steps / have multiple steps during a simulation.	Able to group objects for linking to tasks

3. RESEARCH METHODOLOGY

The specific issue of the LOD within a 4D simulation still requires attention. Primary research has been undertaken to understand issues surrounding the implementation of 4D within the construction industry around the world including the UK, Australia, the US and Iraq (Gledson and Greenwood, 2016; Kim *et al.*, 2016; Hamada *et al.*, 2017; Wong *et al.*, 2011). However, these efforts have focused on the implementation of 4D as it currently stands and did not specifically focus on the issue of the requirements of Level of Detail (LOD_{4d}) of the 4D simulation. Consequently, this study adopted the approach to solicit the opinions of expert users from the industry in order to develop deeper knowledge of the requirements of more dynamic 4D simulations. From this, a framework is proposed to provide an approach to specify the LOD during the planning process and subsequently allow multi LOD simulations to be developed within the 4D session.

An online questionnaire was developed with a survey period between Q3 of 2017 and Q2 of 2018. The target sample population of the study was those who actively engaged in using 4D simulations on a range of construction projects across a section of companies identified from industry case studies. A total sample size of 101 questionnaires were issued with 82 responses being received. Of these responses a total of 61 fully completed questionnaires were received (response rate of 60%) and treated as valid for the purposes of analysis.

The initial part of the questionnaire sought to gain a level of demographic information on the responder, the type and sector of company worked for and the nominal size of the projects the company engaged with. The purpose of this was to identify the role of the participant and to ascertain if any of the results around the use of 4D, and particularly the issue of LOD, was affected by the nature of the company and the type of construction work engaged in. This also included an element of the survey that investigated the role of BIM in the company and particularly the usage of technology to support the BIM process. This focused on the 4D software tools and the project planning tools implemented to provide a backdrop of technology usage. The second section of the questionnaire elicited deeper information on the usage of 4D both from a technological standpoint of who took responsibility for the creation and also how the 4D simulations were used once generated. Building on this, it went on to determine what graphical and temporal level of detail (LOD_{ti}) was used at the moment for each of the use cases of the 4D simulation. The final section of the questionnaire presented the responder with a range of typical construction tasks and asked them to identify to what LOD_{ti} they believed would be most appropriate for that task(s). This section aimed to derive whether there was a need to obtain a range of LOD throughout the lifecycle of a 4D simulation depending on the work package being undertaken at any discrete point. Descriptive statistics were used to develop an overall picture of the use of 4D and the issues surrounding the Level of Detail, including the potential of the 4D simulation to show the construction process at a range of graphical and temporal level of detail. This would then inform and support the development of a framework for the creation of 4D simulations that contain multiple LOD, which can be implemented for the full range of the construction process.

4. RESULTS OF THE QUESTIONNAIRE

4.1 Responder profile

The first stage of the survey analysis was conducted using descriptive methods to gain a level of understanding of the demographic of the responders and the range of work they currently undertake (Figure 1). The highest number of responders fell into the category of BIM Manager/Coordinator/Information Manager (42.6%; n=26), followed by Project Management / Planning (27.9%; n=17), Lead Designer/Engineer (14.8%; n=9), Other management (11.5%; n=7) and Surveyor (3.3%; n=2). The majority of those responding to the survey had worked in the industry for over 15 years, with the median working time having been between 4 and 10 years. The BIM Manager/Coordinator/Information Manager roles showed the highest number of years worked in the sector with most having experience of between 10-15 years. It could be inferred from this that those in the BIM roles have moved into those roles from other specialisms as BIM has become more widespread.

The majority of the respondents to the survey were currently working in the commercial construction sector (59%), followed by civil/infrastructure (34%) and residential (7%). Furthermore, the results demonstrate that the responses came from an even cross section of SME and larger companies with 34% also coming from 'small companies' comprised of 50 people or less.

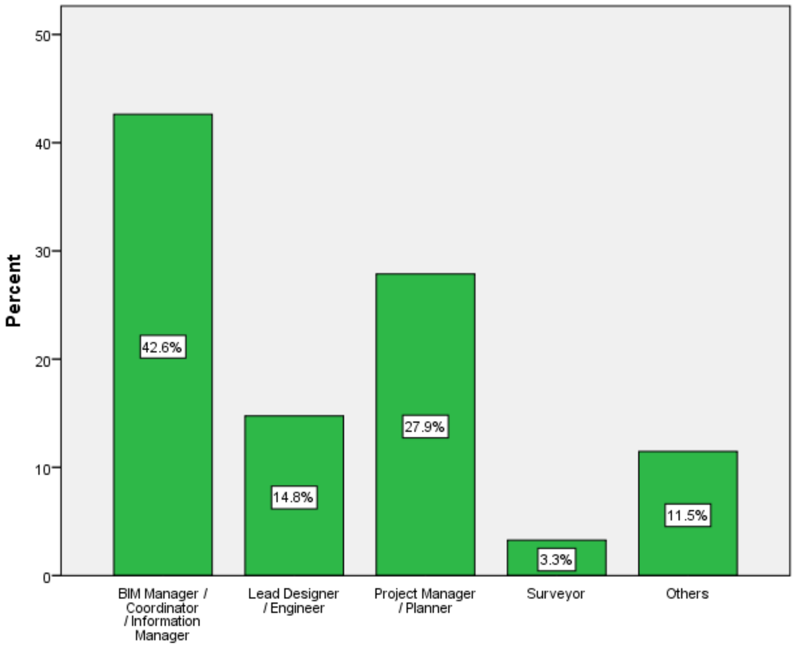

Figure 1: Demographic role of respondents

Within the cross section of responders 92% had engaged in projects where BIM had been used. 75% of these identified the experience they had as being at the UK BIM Level 2 standard and the majority (66%) had been working at this level for between 3-5 years. On the issue of software, the results mirrored those reported annually in the NBS BIM Survey (NBS, 2018), which highlighted Autodesk Revit and Graphisoft ArchiCAD as those most used on BIM based construction projects. However, information was also garnered around the use of 4D simulation tools with Autodesk Navisworks proving the most popular, followed by Synchro and finally Bentley ConstructSim.

4.2 4D modelling issues

The second phase of the questionnaire sought to develop further understanding of the experience of participants with respect to 4D usage and also elicit knowledge around the perception of how 4D simulations are developed to show the more dynamic nature of the construction process. In terms of more ‘traditional’ 1D (time based) project planning, a range of software applications were used with the most popular being Microsoft Project, followed by Primavera, Powerproject and then others which included which included tools such as Microsoft Excel. Of the responses received, it was shown that 62.3% had made use of 4D BIM on construction projects and where it had been used, it had been predominantly applied for purposes of communication with either the client or between contractors and sub-contractors. Other uses included logistics or to enhance the actual planning phase to support development of what-if scenarios during the planning stages (Figure 2). The results broadly concur with those found by Gledson and Greenwood (2016) who found similar uses for 4D which can thus provide a level of credence to the cross section sample within this study.

In order to further investigate this aspect of 4D development, a correlation analysis was undertaken using Pearson coefficient between the usage of 4D BIM and those responding. This demonstrated there is a strong correlation between using 4D BIM for “Communicating the plan to client” (r= +.534), and BIM Managers / Co-ordinators / Information Managers while a strong correlation was presented between Project Managers / Planners and using 4D BIM for “Working package conflicts detection” (r= +.208) and “Site logistic or space planning” (r= +.549). The result could impact on the LOD_{4d} and some of the discussions noted in the previous section whereby it potentially points to the BIM Managers/Coordinators would be involved in the development of lower LOD_{4d} whereas the Project Managers would be involved in higher LOD_{4d}. This could be as expected, however it does have potential to require the project managers to engage in software tools for the development of high LOD_{4d} simulations using decomposition techniques etc.

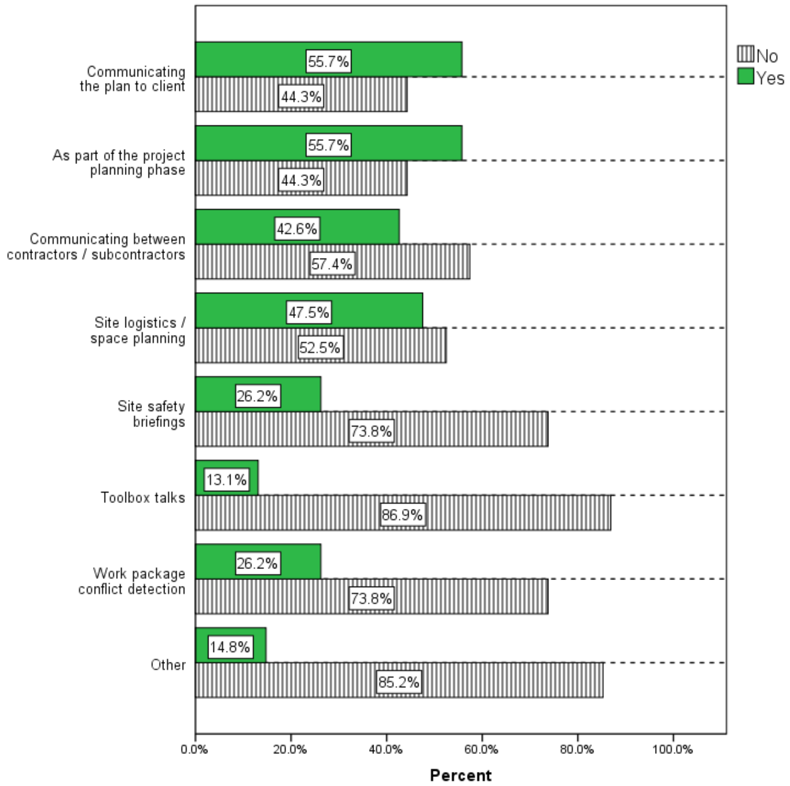

Figure 2: 4D BIM usage in construction projects

As 4D BIM becomes more prominent in construction projects, the responsibility for development of the 4D simulation is also now becoming more fluid. During initial research in the early 21st Century, it was postulated that the construction planner would undertake the development of the 4D simulation and the associated software would become part of the planners' toolbox (North *et al*., 2003). However, as part of this study it was initially hypothesised that as BIM is becoming a specialism and is developing new roles within the industry, so the development and creation of the 4D simulation is falling under the remit of the 'BIM Coordinator / Manager'. The responses to the questionnaire demonstrate that 70% of 4D simulations were actually generated by either BIM (or CAD) technicians or BIM Coordinators / Managers or BIM/4D specialists. 30% were developed by Project Managers or Project Planners. Whilst this still leaves a level of ambiguity, as the initial project schedule of activities were developed by project planners, the development of the 4D and the linking of tasks / sequences to 3D geometric objects was still left to others. Somewhat contradicting this, 68% of responders were of the opinion that the generation of the 4D simulation should be the role of the project manager or project planner. This dichotomy of 4D BIM responsibility is something that requires further in depth consideration outside of the scope of this study but could be attributed to lack of knowledge of current 4D software tools or inability to use current software packages or the lack of direct integration between traditional temporal based planning tools and the 3D technologies associated with the BIM process. With respect to any future LOD_{4d} it could be questioned if the BIM coordinator/manager has the expertise and knowledge of the construction process to develop the 4D model. If not then input would still be required from the planner and/or construction manager to specify the LOD_{4d} from which the simulation could be developed.

Current 4D BIM software technology provides the ability to vary the LOD_{ti} i.e. the time between state changes in the simulation. This can be set to specific intervals within all of the software tools noted in the previous section of the paper. Additionally, several of the existing software tools now provide the ability to either group individual objects or subdivide the geometry of 3D model within the 4D environment to provide the user / planner to develop a more detailed 4D simulation (for example sub-dividing a complete slab generated as 1 geometric object in the BIM authoring tool into subsections for the purpose of planning). This ability to subdivide the geometry to provide greater detail and granularity of the 4D model is critical and 95% of the questionnaire responders agreed that the ability to undertake this provides the ability to produce a more realistic and useful 4D simulation.

However, it still remains an issue to have a single 4D simulation that has the potential to move between various LOD_{ti} as the simulation evolves without having to stop the process and re-specify the time between state changes. 61% believed that the ability to change the LOD within the 4D model was beneficial and could provide more flexibility to the end use of the simulation. The time between state changes varies for various tasks on various projects and is also a subjective factor depending on several variables such as the end use of the 4D model. In order to further understand this phenomenon, the questionnaire asked those who had previously used 4D simulations what LOD_{ti} had been applied. 41% noted that 1-week had been used as the value, 21% stated 1 month had been used, 21% had changed the 4D model on a daily or bi-daily basis and 7% had used the simulation to show changes on an hourly basis. One responder noted that *'…hourly is very common for management and proof of method in advance works'* and another noting that this sometimes changes to facilitate *'…live re-planning'* during a project. Specifically in the area of logistics planning and the use of 4D to alleviate clashes between trades and time space planning during the project, 91% stated that a higher level of graphical detail in the model (LOD_g) and a shorter time period between state changes in the 4D model (LOD_{ti}) were used to undertake a more 'micro' level of 4D. Interestingly it was predominantly the project managers / planners who had responsibility to specify time between state changes for the simulation (58%).

4.3 Example temporal LOD (LOD_{ti})

The responses highlighted above demonstrated that a significant number of the professionals identify the potential benefits of having varying LOD_{ti} within a 4D simulation with nearly two-thirds noting that often it is beneficial to have multiple graphical LOD (LOD_g) and multiple time based on LOD (LOD_{ti}) on a project. This could be particularly true for large projects where some elements may require more detailed planning to enhance issues such as site logistics. In order to gain further insight into this aspect, the third phase of the questionnaire provided a list of 28 nominal construction tasks, which could be represented in a 4D simulation, and asked the responders to note what they believed the optimum temporal stage change would be for each task. The level of graphical detail of the geometric objects was removed from this element so as to understand purely the variance in LOD_{ti} required. From here this could then be used to inform how geometric objects may need to be subdivided.

Figure 3 notes that predominantly responders sought the example tasks to be visualised in the 4D simulation on a daily basis aligning with the results discussed above.

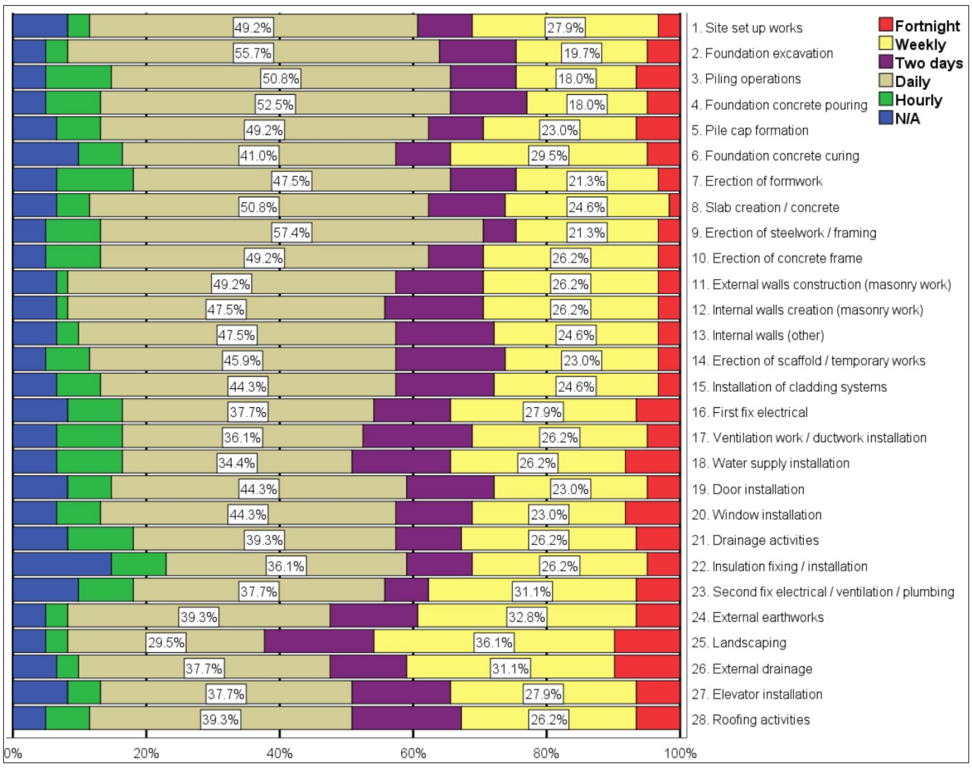

Figure 3: LOD_{ti} in 4D simulations for nominal construction tasks

Whilst this was the most frequent response for all of the nominal tasks, there was also appetite for tasks to be viewed using a range of LOD_{ti}. The majority was either daily or weekly, however there were some instances activities such as piling, formwork and ductwork installation had higher instances of those believing that hourly changes would be beneficial to see. These activities are deemed to be highly dynamic in nature and are also often the cause of time space conflicts during the construction process (Kang *et al.*, 2012; Wu and Chiu, 2010).

Cross referencing these results against the roles of the responders demonstrates that the BIM coordinators generally prefer to view the progress in the 4D simulation on a daily basis and this is mirrored by the project planners and project managers, with some exceptions and anomalies noted above. However, the lead designers lean more towards seeing progress on a weekly basis. This also correlates to the potential use that each of these particular groups sees as the potential main use of the 4D simulation. With planners and mangers seeing the use of the simulation to support construction work and the designers seeing benefits of the simulation as a more communication tool, particularly for clients.

5. DISCUSSION

The purpose of the survey was to assist in an ongoing piece of research to develop a holistic framework and subsequent methodology for the standardised approach to specify the Level of Detail for 4D simulations (LOD_{4d}). Initially a conceptual framework was derived (Figure 4) which bought together the key elements of current approaches to 4D simulation and some of the key issues that would impact on the development of the LOD of 4D simulations (adapted from Butkovic and Heesom, 2017).

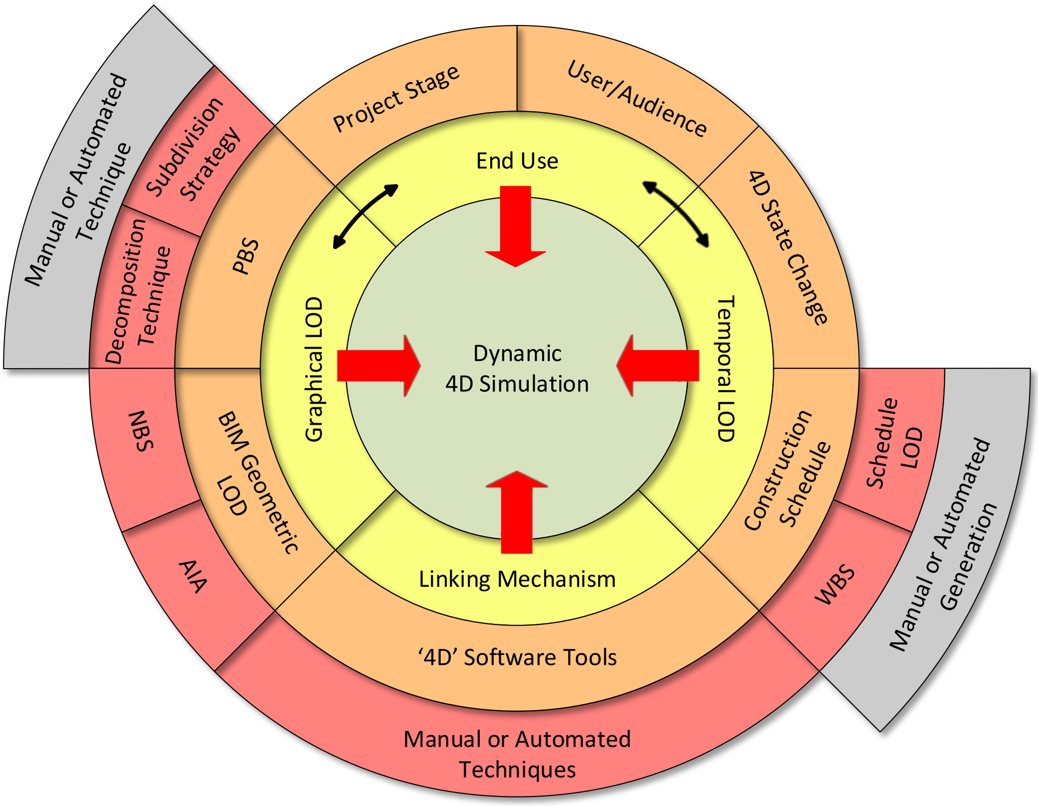

Figure 4: Conceptual Framework for dynamic 4D simulations
(Source: adapted from Butkovic and Heesom, 2017)

The framework identified 4D primary factors which impact the development of a dynamic LOD_{4d} simulations. The *End Use* of the simulation will impact the LOD_{4d} and this can be reflected by the stage of the project and the user of the simulation. For example, early concept stage simulations would potentially require less detail and may be shown as part of the planning approval. Later stage simulations may be used by the contracting team and require more detail. The *Temporal LOD* encompasses the temporal stage change of the simulation and the breakdown/detail of the construction schedule. The amount of detail in the construction schedule can impact this directly. Whilst the construction schedule is generally developed by the construction planner at various stages of the project, there are examples of work, such as Faghihi et al. (2014) which investigates the application of automated generation of schedules and this is something that could impact the LOD_{ti} development of 4D in the future. The *Graphical LOD* will encompass the amount of detail contained within the geometry of the BIM aligning to prevailing standards such as the AIA LOD in the USA and the NBS LOD approaches in the UK. The geometric breakdown of the product breakdown structure for a 4D simulation is based on how the elements are decomposed and the strategy used to do this. This is often a factor of the construction approach adopted by the planner. Generally this is undertaken manually either within the 4D tool, or as part of the BIM creation in the authoring software, however there have been examples of approaches (Heesom, 2006) where this is undertaken using a more automated approach. The *Linking Mechanism* relates to the existing technology solutions which provide the ability to link the graphical data and schedule information.

The data received from the questionnaire survey was comprised of a range of professionals who were categorised into those whose specialism was BIM, those who were designers, project planner/management and surveyors. This gave a cross section of those who currently utilise 4D BIM for a range of applications. It is becoming clear from the results of this survey that the development of 4D models is falling under the remit of the BIM specialists more than the construction planner. This itself is worthy of note, as from the early days of 4D development, it was hailed as a tool to support construction planning and specifically the construction planner. In order to produce a 4D simulation that contains the appropriate level of detail input would be needed from the construction planner and the construction management team to specify the LOD_{ti} and, if the geometry is to be divided or grouped to give a more realistic simulation, then a construction strategy/methodology would be required to support updates to the 3D geometry. It may be possible in the future to automate some of these processes with the advances in AI and build upon some of the early work on construction strategies and zoning.

The ability to generate more ‘realistic’ simulations of the construction process is controlled by the ability to a) view realistic graphical representations of individual objects during construction and b) better control the time between state changes of the 4D model (LOD_{ti}) which then has an impact on how individual geometric objects from the BIM are subdivided. The graphical LOD of the BIM objects in the design model will play a part in governing the representation of single objects in the 4D simulation. However, some previous work has identified that for the purposes of site logistics planning and management, a low LOD of geometric objects is adequate (North *et al*., 2003). The overwhelming response from the questionnaire noted that the ability to subdivide the geometry to show a more granular level of progress in the 4D simulation was beneficial. Linking this to a schedule with a higher level of detail will then provide a more detailed 4D simulation which, from the results, planners see as beneficial during logistics planning of site operations.

Some work has previously noted that the current use of 4D is actually a visualisation tool to review the already developed construction plan rather than a tool used within the planning process (Zhou *et al.*, 2009) and these results may corroborate this theory but further work is needed in this regard. The range of software tools to support the development of 4D is still limited, primarily down to the very specific nature of the task and the uses of 4D at the present time are still very much focused on the communication to various stakeholders in the construction process. This is still a significant benefit, however it appears that the opportunity to move beyond this usage into the application for detailed briefing, site logistics management and interactive project planning is yet to be realised and as this moves forward, it will become necessary to specify the LOD of the 4D simulation in the same way that the LOD and LOI are specified for models in the BIM process.

It is based on the above and building on the initial conceptual framework, that the wider remit of this work proposes to create a new framework to support the specification of the LOD of 4D simulations (Figure 5). The overall 4D LOD (LOD_{4d}) is a unification of Level of Graphical Detail (LOD_g) and the Level of Temporal Detail (LOD_{ti}) which details the time required in the simulation between state changes. However, the graphical LOD should be a combination of the detail of the geometry representing the final product (i.e. the BIM LOD - LOD_{geom}) and the Level of Detail of granularity (LOD_{gran}), which depicts how the object should be decomposed during the linking process.

It is also noted that temporary works are also now becoming a key factor in the use of 4D for more effective construction planning. Whilst Cassano and Trani (2017) discuss the level of geometric detail of temporary works elements when included in a BIM authoring tool, work such Kim and Cho (2015) or Cheng and Chang (2018) detail how temporary structures or temporary laydown areas can be included in the 4D simulation to provide a more robust and realistic view of the construction simulation. Furthermore, several of the commercial 4D tools available, such as Navisworks and Synchro, provide the ability to animate objects within the 4D simulation and this is being used to highlight route paths of plant or turning envelopes of cranes. Very often, this serves as a more aesthetic purpose to provide a level of graphical 'realism' to the simulation, however it is noted that in Autodesk Navisworks the ability exists to detect clashes between animated objects in a 4D environment. The results of the survey undertaken in this study do highlight there is more limited appetite for the use of state changes and LOD_{ti} on an hourly basis which may be most suited to the animation of plant objects. However, this is something that could be included as part of the granularity LOD_{gran} aspect of the LOD_g specification and as such the framework highlights the issue of temporary works and how this is fed into the 4D simulation. Often these construction/erection and deconstruction of objects associated with temporary works are additional to the BIM geometry and so also need to be considered. This will require specifying the geometric detail of any objects and also the granularity of the geometry as it is being constructed - for example the erection of scaffolding over several days. The inclusion of temporary works may also require the addition of tasks into the schedule to facilitate the development of 4D objects.

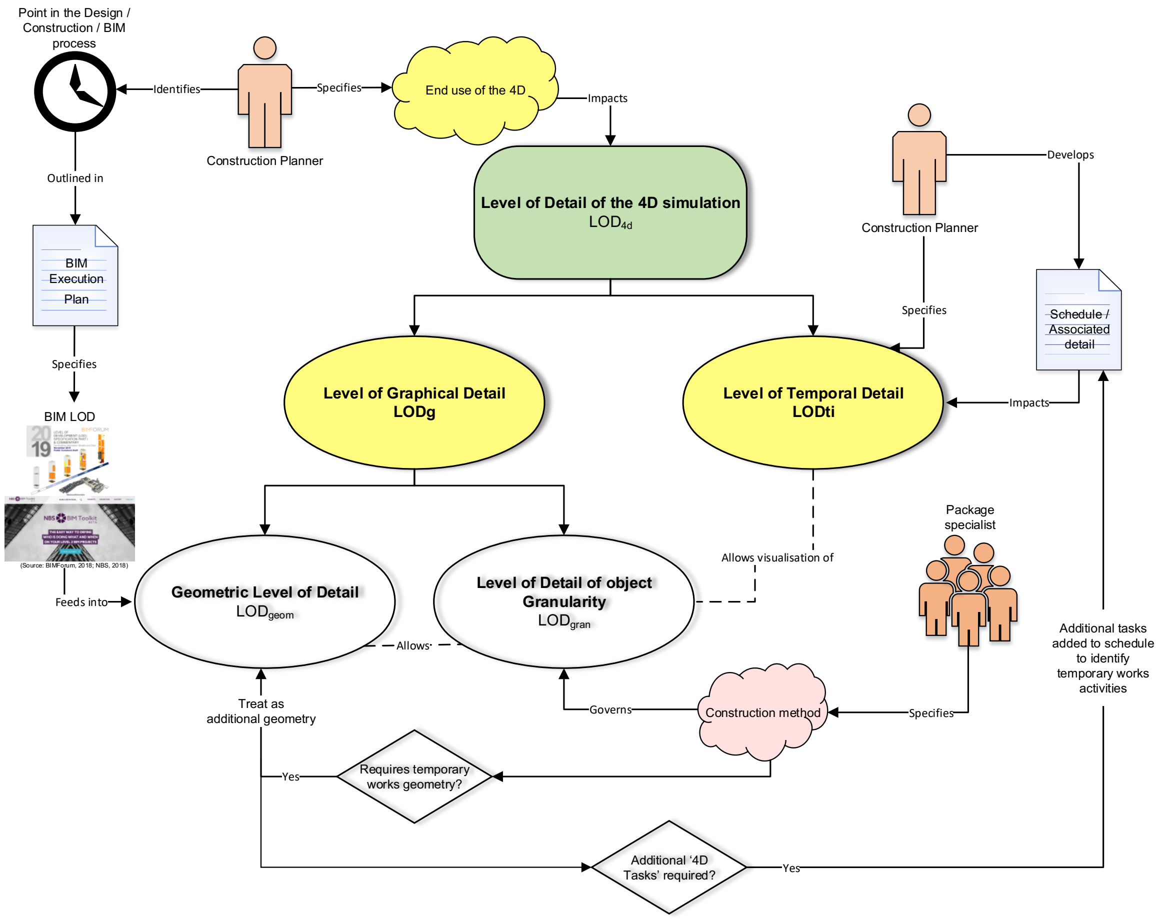

Figure 5: Framework for specifying the LOD of a 4D simulation (LOD_{4d})

5.1 Framework application

Building on the framework, the findings from literature and the results of the questionnaire a LOD_{4d} schematic is proposed to provide initial guidance on how each of the constituent LOD factors link and inform some example use cases (Figure 6). There are a range of factors that can influence the level of detail including the schedule detail, the time between state changes and the detail of the geometry which can then be granulated. Results show that 4D is currently used significantly for client briefings and marketing often this will require a low level of temporal detail with some high graphic content to 'sell' the scheme. As a further example, where 4D is used for workspace planning and logistics a highly detailed schedule can be used, linked with a detailed BIM model which can then be subdivided further and visualised using a high level of temporal detail.

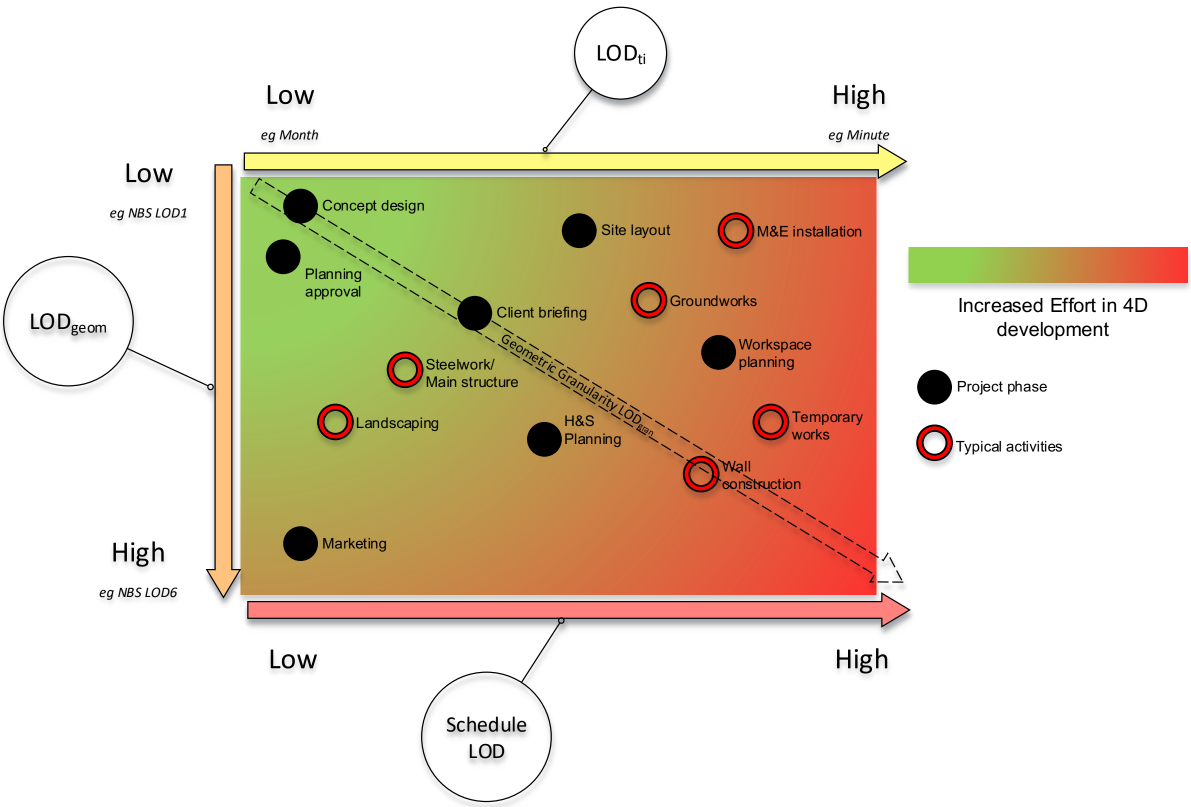

Figure 6: LOD$_{4d}$ schematic and use cases

By providing the ability to begin to specify the LOD of a 4D simulation, the potential now exists to configure the simulation for a specific purpose. In much the same way as the BIM process can now begin to specify the LOD and LOI tailored to the use of the model and the data required by the client, so the 4D simulation can be tailored to suit the project and / or specific work packages within the project. This will remove the 'one size fits all' approach of many current 4D simulations and move to support the notion reported above from questionnaire responses, which highlighted the benefit of being able to change the LOD within the 4D model during the process.

Whilst 4D is often seen as a tool for the main contractor and to manage site activities, it also needs buy in from the sub-contractors to ensure that the graphical and temporal information is available to meet the needs. The effective development of a 4D model encompasses the geometric models of the designers, main contractors and the specialist sub-contractors. In addition, the schedule for each of the work packages is required at a relevant level of detail. It is for this reason that it proposed that the issue of 4D data requirements for each stage of the project is included as part of the BIM execution plan for the project. In alignment with PAS1192-2 (BSI, 2013) the BEP highlights the data structure and requirement for each stage of the project and this can now include issues around LOD$_{4d}$. To ensure the correct data is available, an addendum to the BEP specifically focused on 4D requirements is proposed as future work, based on the outcomes of this study. This will provide a LOD$_{4d}$ matrix, similar to the Model Production Delivery Table (MPDT) utilised in the UK BIM Level 2 standards.

As noted in Figure 6, the effort required to produce higher LOD$_{4d}$ simulations is increased. Noting some of the examples provided, it is also postulated that higher LOD$_{4d}$ may only be required for certain operations, workpackages or certain periods of time throughout the project period. For example, a confined area which requires several contractors to work together (such as M&E and finishes) may require a higher LOD$_{4d}$ but only for a short period. The period immediately prior to and following this may be serviced with a lower LOD$_{4d}$. In these circumstances, it would be beneficial to have the ability in the simulation to have multi-LOD and associated data such that a single 4D simulation can run using multiple LODs throughout. The ability to move between LOD$_{ti}$ and LOD$_{gran}$ within a 4D simulation is required to be seamless. At the present this would have to be undertaken by stopping and reconfiguring the simulation for a certain period. This is a current technical limitation of the software tools available. This 'federated 4D simulation' would mean that detailed information would be required as specified in the BEP to support the project requirements. To further the concept, and building upon the collaborative nature of BIM, the development of the LOD for project could be undertaken in a multi-disciplinary collaborative environment. The work of Zhou et al. (2010) and Zhou et al. (2014) developed the philosophy of collaborative 4D development and this approach could support the generation of LOD_{4d} requirements at different stages of the project.

With the above in mind, the critical issue of cost features in the development of 4D simulations with varying LOD. The return on investment of utilising BIM is a complex area and it is difficult to derive an exact metric (Azhar, 2011). The lack of a definitive return on investment has been identified as a key barrier to the uptake of BIM (Kim et al., 2016) whilst Ahmed et al. (2014) noted that specifically a lack of real world understanding of ROI of 4D was also hampering the uptake. Ghaffarianhoseini et al. (2017) noted the benefit of BIM in reducing schedule based delays in construction, the study proposed that much further work was needed to actually derive an exact ROI. The issue of return on investment is critical when discussing the issue of LOD of a 4D simulation. As postulated in Figure 6, as the constituent parts of the LOD_{4d} increase, so does the effort required to generate the 4D simulation. This subsequently has an impact on the amount of time and the cost in developing a 4D simulation with a higher LOD. Noting that some studies have purported ROI of using BIM of significant values (Giel and Issa, 2011) there have been no substantial metrics to measure the same for 4D and specifically with the focus being on the ROI associated with the LOD of the 4D simulation. Relating this to the issue of the amount of effort required to produce a higher level LOD_{4d}, the issue of cost also supports the notion of only developing higher LOD simulations when it is required rather than a blanket approach for the entire project. These issues are proposed as an area of future work that will align to the work reported here to give a clearer indication of the value proposition associated with higher LOD_{4d}.

6. CONCLUSIONS AND FUTURE WORK

This paper has provided further detail on the issue of Level of Detail of 4D simulations, which hitherto has been an area with a paucity of research. Level of detail of 4D is a complex subject as it relates to a number of factors including the level of geometric detail, the level of detail of the temporal state change within the simulation and the potential use of the simulation which can govern how dynamic and realistic the simulation should be. The lack of research and standardised frameworks in this area has lead to simulations often defaulting to one single temporal LOD throughout a project and limited use of the ability to change the granularity of the geometry to match the needs of the end use. This work has presented an initial framework and schematic to support this backed up by the results of a survey of industry professionals who utilise 4D on real construction projects. At the moment the development of a 4D simulation can be seen as an asynchronous process, however the framework proposed here goes someway to resolve this issue.

Further work will see this framework being developed into a proposed 4D LOD specification for a construction project, to sit alongside the BIM execution plan (BEP) of a project in order to provide a more formalised use of 4D simulations. This will provide a LOD_{4d} matrix similar to the Model Production Delivery Table (MPDT) utilised in the UK BIM Level 2 standards. Additionally, work will seek to address the technological methodologies to combine multiple LOD_{gran} and LOD_{ti} within a single simulation environment to allow multiple LOD_{4d} to occur within a single project 4D simulation. At present some 4D software tools allow the decomposition of geometric objects within the creation environment, by allowing the subdivision of geometry but this is still a very manual exercise and not dynamically linked to the specification of a LOD_{ti}. The ability to do this without the need to created numerous additional tasks will further support the creation of dynamic multi-LOD 4D simulations.

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