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A method for discrete event simulation and building information modelling integration using a game engine

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Abstract. Building Information Modelling (BIM) and Discrete Event Simulation (DES) are tools widely used in the context of the construction industry. While BIM is used to represent the physical and functional characteristics of a facility, DES models are used to represent its construction process. Integrating both is beneficial to those interested in the field of construction management since it has many potential applications. Game engines provide a human navigable 3D virtual environment in which the integrated BIM and DES models can be visualised and interacted with. This paper reports the experience obtained while developing a simulator prototype which integrates a BIM and a DES model of a single construction activity within a commercial game engine. The simulator prototype allows the user to visualise how the duration of the construction activity is affected by different input parameters interactively. It provides an environment to conduct DES studies using the user's own BIM models. This approach could increase the use of DES technologies in the context of construction management and engineering outside the research community. The presented work is the first step towards the development of a serious game for construction management education and was carried out to determine the suitable IT tools for its development.

Keywords: building information modelling; discrete event simulation; game engine; serious game; construction management

1. Introduction

The construction industry is becoming increasingly demanding as we try to confront the challenges that the world is facing. The many benefits of Building Information Modelling (BIM) are becoming apparent to stakeholders, who are turning to this and other new technologies in an effort to meet the demands of the industry.

Game engines have also drawn the attention of researchers in the construction field, as they provide ways to achieve immersion in visualisation due to their compatibility with mixed reality technologies, ubiquity as they offer multi-platform deployment, high-quality graphics and other characteristics. Game engines have been used to deliver software solutions faster and cheaper by taking advantage of the available resources that they include regardless of the developer's programming experience (Trenholme and Smith 2008, Neto and Brega 2015, Osorio-Sandoval *et*

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al. 2017).

Game engines provide an excellent platform for virtual environments and coupled with the models created through the use of BIM tools, show great potential for presentation, visualisation, education and simulation (Bille *et al*. 2014).

Integration of BIM models and game engines has been previously studied and its proposed applications are many, from mixed reality architecture visualisation to utilisation of BIM models as game content, which brings the possibility of using real world-based game scenarios able to take advantage of all the information contained in them.

Some examples of this integration in the context of education are the Serious Human Rescue Game, a serious gaming approach based on BIM for the exploration of the effect of building condition on human behaviour during the evacuation process, which integrates the "BIM-game engine", a custom game engine and Autodesk Revit (Rüuppel and Schatz 2011); a BIM-Game prototype that supports design-play as a new design process, offering a real-time, interactive, photo-realistic visualisation with physical simulation of gravity and collision detection as well as behaviour simulation through the modelling of the virtual user (Yan *et al*. 2011); the role-playing serious game for building sustainability education, which is based on Autodesk Revit, Maya and the Unity game engine (Dib and Adamo-Villani 2013); and the gaming prototype developed with BIM inputs for teaching and research in the field of design for sustainable ageing (Wu and Kaushik 2015).

There are several strategies to integrate BIM with game engines. Both Bille *et al*. (2014) and Wu and Kaushik (2015) exported models produced in Revit to filmbox (fbx) and reported that the resulting model did not carry over any colours or textures if being read directly by the Unity game engine, which they fixed by first further processing the fbx file in Autodesk 3ds Max, although this would not handle the importation of non-geometrical meta-data (Bille *et al*. 2014). The same procedure was followed by Natephra *et al*. (2017) to import BIM models into the Unreal game engine. An alternative approach is exporting the Revit model via Open Database Connectivity to a database and reading model information from it directly into Unity, which would also result in the loss of model element material's property during the transition (Wu and Kaushik 2015). In the current version of the Unity game engine it is not possible to import a file in the Industry Foundation Classes (IFC) format.

Besides BIM and game engines, Discrete Event Simulation (DES) techniques have been widely used in the construction industry context. Examples of its applications are studying the impact of variables on the productivity or duration of construction projects (Ebrahimy *et al*. 2011, Osorio Sandoval *et al*. 2016); used as a tool for decision making and resource management (Zayed and Halpin 2001, Zhang *et al*. 2008); and studying and improving construction operations or processes (Rahm *et al*. 2016), among others. However, it has been argued that due to the way DES models show their results, they have not yet been fully embraced as a valuable tool by stakeholders in the construction industry. In fact, it is generally agreed that the use of simulation technologies in the construction domain is mostly limited to research purposes (AbouRizk *et al*. 2011).

In this paper, a simulator prototype which integrates the DES model of a construction activity and a BIM model that represents the physical characteristics of the same construction activity within a commercial game engine is presented. The prototype allows the user to visualise how the duration of a single construction activity is affected by different input parameters.

The main purpose of this research is to explore the possibility of using this integration as the core of a serious game for construction management education. In addition, it is intended to provide an alternative way to study construction activities digitally.

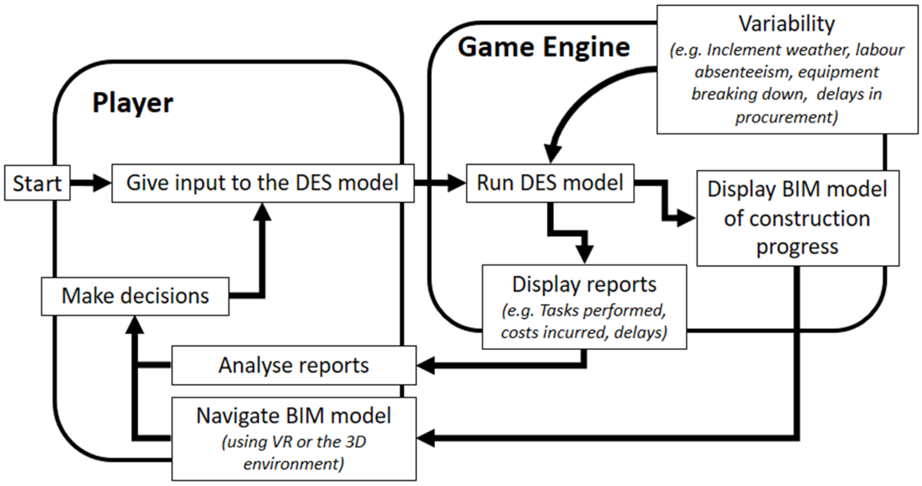


Fig. 1 Interaction of the player and the game engine

2. Project background

In most construction engineering and management courses offered by Universities, traditional lectures are insufficient to equip the students with skills to solve problems encountered in the real world of construction or to convey complex engineering knowledge effectively (Al-Jibouri and Mawdesley 2003). Moreover, lectures do not provide the students with hands-on decision-making experiences in applying newly gained knowledge (Dzeng *et al*. 2014).

As a result, construction engineering and management graduates do not gain practical experience or any relevant skills until they enter the field. In pursuit of covering the gap in knowledge and experience between the graduate engineer and the real-world construction engineer, serious games in construction management education have been the subject of many research and development efforts.

Serious games are an ideal solution for learning an activity when actual experience is not practical, possible, profitable or sensible, as they provide students with an opportunity to experiences an activity or process that cannot be replicated through traditional teaching approaches and is too hazardous, costly or time consuming to be performed as a teaching exercise (Long 2010). In construction management, there is an increased uptake of serious games (Oo and Lim 2016).

As well as serious games, the integration of project management tools based on BIM can help educators to develop construction management class projects that simulate realistic practical situations. BIM-based tools allow students to learn better how to apply different formal construction management methods to specific project contexts (Peterson *et al*. 2011).

Combining serious gaming with BIM-based tools can be a good approach to cover the lack of real life experience and practice in construction management that civil engineering students have.

As part of the design process of the proposed serious game, it has been decided to model the construction process of a facility using DES and its physical characteristics using BIM. The player would be able to modify the input parameters of the DES model and visualise the results of the decisions taken by interacting with the resulting BIM model that would display the construction progress of the project. Figure 1 shows the interaction between the player and the BIM and DES models integrated within a game engine in the proposed serious game.

We aim at transferring a construction programme from a scheduling tool (e.g. MS Project) and its corresponding BIM model into the DES framework in order to visualise the progress of the project in terms of time and cost with different input parameters in the DES model (e.g. number of resources allocated to each task, location of materials in the construction site, weather sensibility of tasks, etc.).

The simulator prototype presented in the following sections is the first step towards the development of the serious game for construction management education depicted above.

3. Methodology

The presented prototype consists of the interaction of two different kinds of models (BIM and DES) of the same construction activity, namely, masonry walls with concrete blocks, which was chosen because it is one of the most common in industry. Although in the 20th century masonry was displaced for many applications by steel and concrete, it remains of great importance for walls in low and medium rise buildings and for internal walls and cladding of buildings where the structural function is met by one or other of these newer materials (Hendry 2001). Moreover, in the context of housing projects in South East Mexico, masonry walls with concrete blocks is one of the most representative construction activities in terms of the impact of its direct cost on the total cost of a given project, according to a comparison of the cost estimates of several housing projects in that region, in which, on average, the direct cost of this activity represented 8.28% of the total cost of each project, surpassed only by rubble stone masonry foundations and pre-cast beam and block slab roofing, whose direct costs have higher impacts on total cost but are not as common (Osorio Sandoval 2015).

BIM was used to model the physical characteristics of the result of the selected construction activity. This model consisted simply of the masonry walls of a one-storey house. On the other hand, DES was used to model the construction process of the activity. This model represented the logic in which the simple tasks that make up the activity, the resources involved in its process and some rules of thumb to consider are related. The DES approach was selected because it is the most suitable approach to model construction operations since events only occur at specific points in time (Hassan and Gruber 2008).

According to Martinez (2009), the appropriate steps for DES studies in construction engineering and management include defining the model for the activity by establishing its level of detail, selecting the elements used to represent the real system and capturing the logic appropriately; collecting and synthesizing data about the activity to suit the model; verification and validation of the model; designing and executing simulation experiments; analysing the output of the experiments; documenting the results and using them for decision making.

The presented prototype provides an environment to conduct DES studies using a valid predefined model in which to design and analyse simulation experiments. In this prototype, the DES model takes parameters both from the BIM model and the user's input. For example, one of the simple tasks in the DES model is moving the concrete blocks from the site storage to where they are needed. One of the resources involved in the task is the concrete blocks. From the BIM model, the area of the walls is used to calculate how many are required to complete the activity and the DES model creates one entity to represent each block. An example of a rule of thumb to

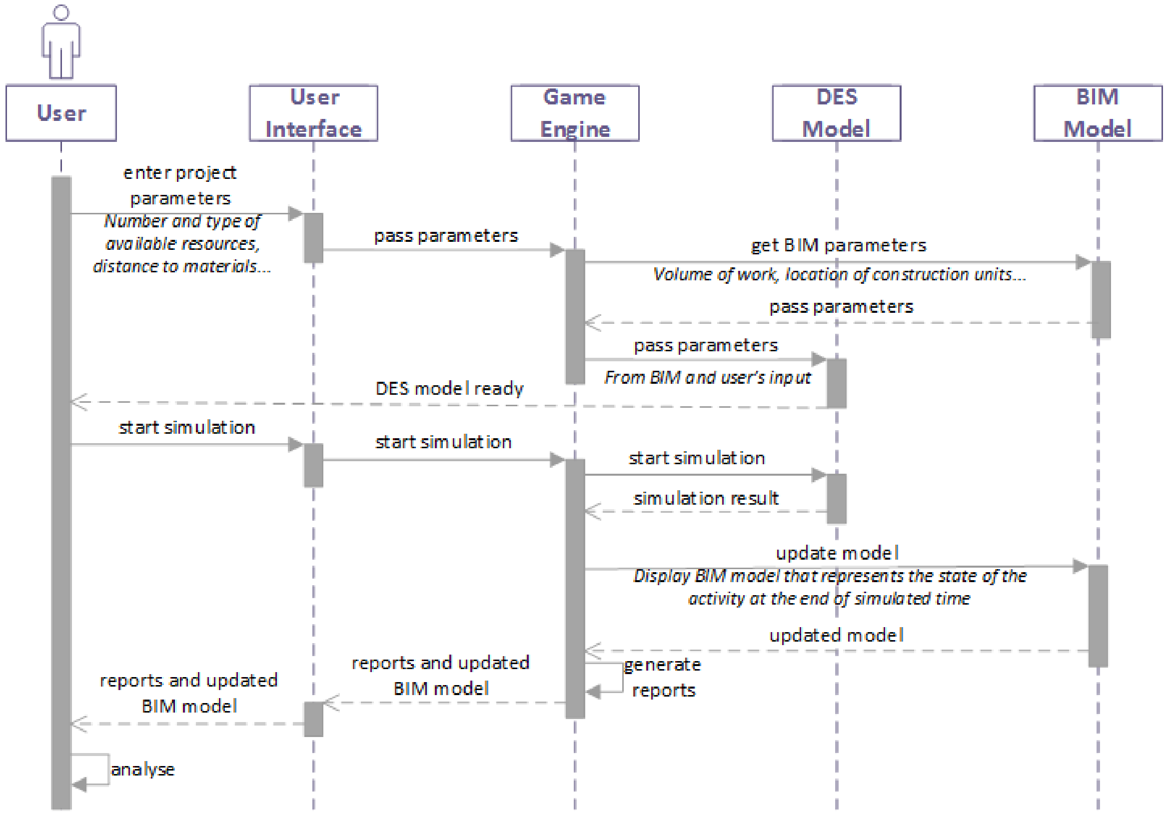


Fig. 2 Prototype sequence diagram

consider could be to perform this task using a wheelbarrow with a capacity of 8 concrete blocks. Consequently, the DES model would make batches of 8 entities to represent this.

Another resource is the labourers that move the wheelbarrows. The user inputs how many are available to perform the task and the DES model creates one server to represent each. This would mean that the model considers that there is a wheelbarrow available for each labourer involved in the task, if we consider the rule of thumb stated earlier. However, this can be modelled differently to increase the level of detail of the system.

Finally, for this task the distance between the site storage and the location of the walls is also of interest. The user inputs the location of the site storage, whereas the location of the walls is a parameter taken from the BIM model. Using both locations, the distance that the wheelbarrows need to be moved is calculated and the productivity of the labourers moving them is affected by it in the DES model.

The approach described above intends to allow users to import their own BIM models into the prototype while taking advantage of the proposed DES framework.

The BIM and DES models were integrated within a commercial game engine to provide a virtual environment in which the user can change some of the input parameters of the DES model, run a simulation with those parameters, analyse its results and visualise and interact with a BIM model that represents the state of the activity at the end of the simulated time. The interaction between both models, the game engine and the user is illustrated in Figure 2.

4. Implementation

4.1 Software tools

Game engines are part of the trending technologies used by researchers and developers in the serious games domain as they provide a way to achieve immersion, ubiquity and quick game content development. While there are several commercial off-the-shelf game engines available in the market, a literature review on serious games with focus on technology application showed that 57% of the developers that use game engines in their work have a preference for the Unity software. Amongst the reasons for choosing Unity over other game engines, the most relevant appear to be functionality, multi-platform development, availability at no cost and capability of interacting with major 3D tools and file formats (Osorio Sandoval *et al*. 2017). Moreover, integration of BIM models and game engines has been previously studied and some successful attempts to import BIM models authored in Autodesk Revit into Unity can be found in literature (Bille *et al*. 2014, Dib and Adamo-Villani 2013, Wu and Kaushik 2015). Considering this, for the development of the presented prototype it was decided to use Unity as the game engine and Autodesk Revit as the BIM authoring tool.

Although there are many tools in the market to create DES models, their implementation within the Unity game engine would not be practical, if at all possible. It was decided that the best approach to perform a DES in the game engine would be through scripting alone. A review of the state of the art in open source DES software used for decision support in operations research was performed by Dagkakis and Heavey (2016), who reported that the only tool found written in the C# programming language, which is supported by Unity, was SharpSim, a software library developed by Ceylan and Gunal (2011). After testing its compatibility with Unity's C# compiler, it was decided to use SharpSim to create the DES model for the simulator prototype.

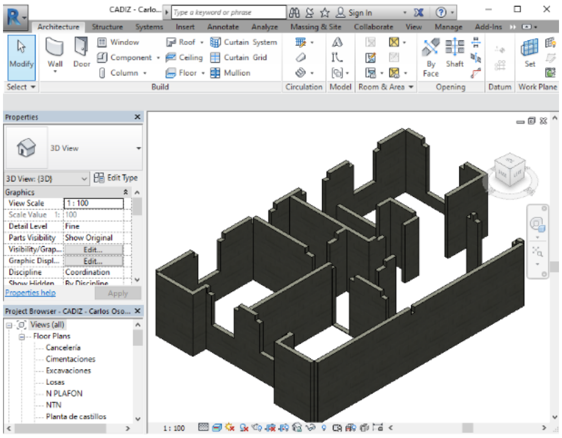
An important step in building a DES model is to select the probability density function (and its parameters) that represents the duration of each task most appropriately. Thus, it is necessary to perform goodness of fit tests to a set of data of possible durations for each task. To perform these tests, it was decided to use the software EasyFit of Mathwave, which can carry out the goodness of fit tests of Kolmogorov-Smirnov, Anderson-Darling and Chi-Squared and has support for over 55 distributions (MathWave Technologies 2004).

Finally, Unity allows integration with Microsoft's integrated development environment (IDE) Visual Studio, which provides a more sophisticated C# development environment with features like smart auto-completion, computer-assisted changes to source files, smart syntax highlighting and more (Unity Technologies 2017). For this project, Visual Studio was used as the IDE tool.

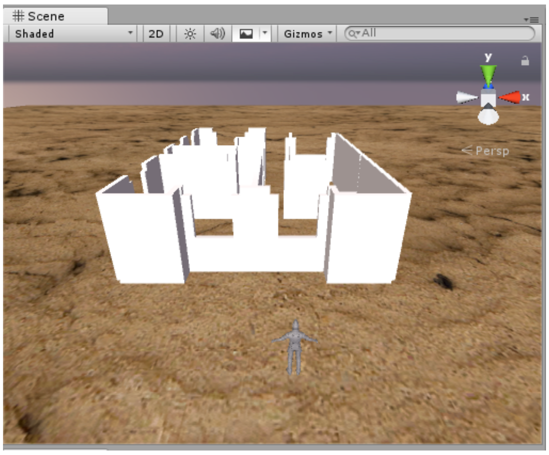
4.2 Integration of building information modelling and the game engine

A BIM model representing the masonry walls with concrete blocks of a one-storey house was made using Autodesk Revit. The BIM model was exported into a filmbox file (fbx) and then imported directly into Unity. Each element in the model can be treated as an independent game object. Figures 3a and 3b show the model in Revit and in Unity respectively.

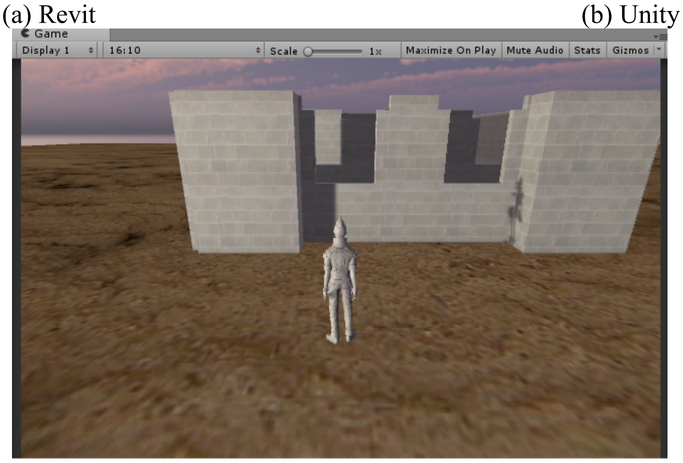
Although previous research suggested a further processing in Autodesk 3ds Max of BIM models authored in Autodesk Revit before importing them into Unity (Bille *et al*. 2014, Wu and Kaushik 2015), material library files (mat) can be applied to any game object within Unity and its properties can be tweaked in the inspector to achieve the desired texture. Using the latter approach,



(a) Revit



(b) Unity



(c) Unity post processing

Fig. 3 Concrete block walls model in Revit and Unity

the model was processed within Unity to achieve a more realistic view. Figure 3c shows the model processed in Unity.

Non-geometrical meta-data that is lost due to exporting the model into fbx can be assigned back to the model elements that may require it through scripting. This method was used to assign different tags to each one of the walls that were modelled in order to differentiate them from one another.

4.3 Discrete event simulation model of the selected construction activity

The DES model of the masonry walls with concrete blocks was built with SharpSim (Ceylan and Gunal 2011) by including the SharpSim library as a reference within the IDE Visual Studio and coding in the C# programming language.

4.3.1 Outline of the DES model

The construction activity of masonry walls with concrete blocks was broken down into four

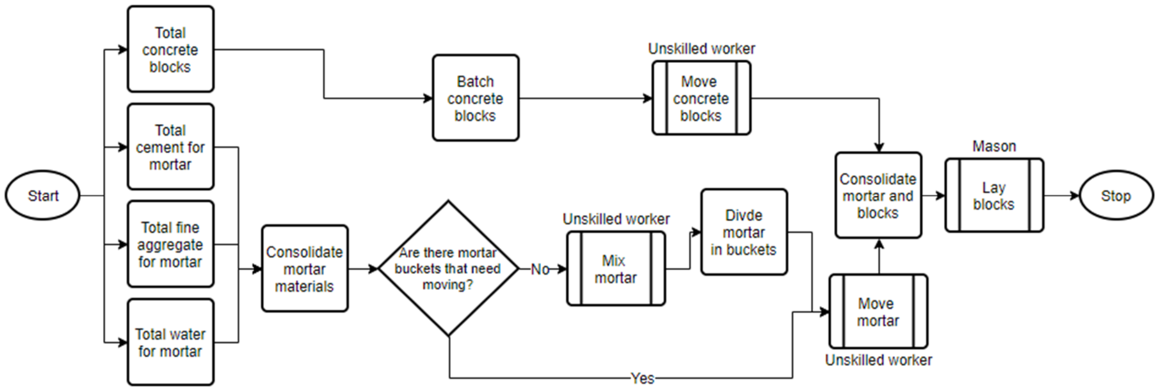


Fig. 4 Flow chart representing the outline of the DES model

different simple tasks: Carrying concrete blocks, mixing mortar, carrying mortar and laying concrete blocks.

Other tasks that could also be considered as part of this construction activity, such as squaring the outline of walls with mason lines or the installation of scaffolding, were disregarded in this version of the prototype.

The following rules were established to outline the model:

- The crew performing the activity will consist of two types of workers, namely, masons and unskilled labourers.
- All the simple tasks will be assigned to unskilled labourers except for the laying of the concrete blocks, which will be responsibility of masons.
- All the required materials will be available at the start of the simulation.
- The task of carrying the concrete blocks will be executed using a wheelbarrow with a capacity of eight concrete blocks.
- The task of mixing mortar will result in a volume of seven buckets of mortar.
- After the task of mixing mortar is executed for the first time, it will not be executed again until the resulting seven buckets of mortar have been moved.
- Only one bucket of mortar will be moved each time that the task of carrying mortar is executed.
- One bucket of mortar will be used to lay two wheelbarrows of concrete blocks.

The logic with which these tasks and rules are related is depicted in Figure 4.

The flow chart above can be explained as follows:

- When the simulation begins, different entities representing the different materials required by the construction activity are created. Each entity represents a single unit of its corresponding material, for example, an entity of type concrete block would represent one concrete block, while an entity of type water for mortar would represent one bucket of water. Enough entities to complete the total volume of the construction activity are created at the same time without delaying the simulation clock. This is to represent the availability of all the required materials at the beginning of the simulation. However, this can be modified to include the process of procurement of materials in the model.
- Entities flow to the next events where they are processed and change to new entities representing groups of materials. For example, concrete block entities are batched it groups

of eight according to the rules stated before and a new entity of type wheelbarrow of blocks will continue to flow on the model. This process also occurs without delaying the simulation clock. In this prototype, the duration of the loading (and unloading) of the wheelbarrow and the duration of carrying the separate mortar materials to mix them are included in the duration of the tasks of carrying blocks and preparing mortar respectively. Nevertheless, these processes can be considered as separate tasks and their durations can be specified separately in the model to increase its level of detail.

- When an entity reaches a task event, it will be processed and the simulation clock will be delayed by a random number based on the parameters of the probability distribution that fits the task's set of possible durations only if there is an idle resource of the type required by the task. Otherwise, the entity will be added to the queue of the corresponding resource and it will be processed until a resource of that type becomes available.
- The decision block in the flow chart works as a valve to prevent the mixing of new mortar if there is still mortar waiting to be moved to where it is needed. Although there may be an entity that requires processing in the task of mixing mortar, it will remain in the queue of the corresponding resource until there are no more entities that require processing in the task of moving mortar.

4.3.2 Duration of tasks

Through field observation, data was collected for each one of the tasks that are part of the selected construction activity. The data collection included the time effectively used to complete the task, the amount of work executed during the observed time and the amount and type of workers involved in the execution of the task. The field observations took part in fourteen small and medium size housing projects carried out by a contractor in South East Mexico between 2013 and 2015 (Osorio Sandoval *et al*. 2016).

Using these data, several labour productivity values were calculated for each task using equation 1 (Project Management Institute 2013).

$$P_{ij}^{k} = \frac{Q_{ij}}{D_{ij} * N_{ij}} \tag{1}$$

where P_{ij}^{k} is the productivity of the task; Q_{ij} is the total amount of work executed during the observed time; D_{ij} is the duration of the observation; and N_{ij} is the number of workers involved in the execution of the task.

For each productivity value obtained, a possible duration for each task was determined using equation 2, which is derived from equation 1.

$$D_{ij} = \frac{Q_{ij}}{P_{ij}^{k} * N_{ij}} \tag{2}$$

where D_{ij} is the duration of the task; Q_{ij} is the total amount of work executed during the execution of the task; P_{ij}^{k} is the productivity of the task, previously obtained; and N_{ij} is the number of workers involved in the execution of the task.

Q_{ij} can be calculated for each task by following the rules used to outline the DES model, which were presented in section 3.4.1. For example, since it was established that the wheelbarrow for carrying concrete blocks would have a capacity of eight blocks, Q_{ij} for that task would be eight.

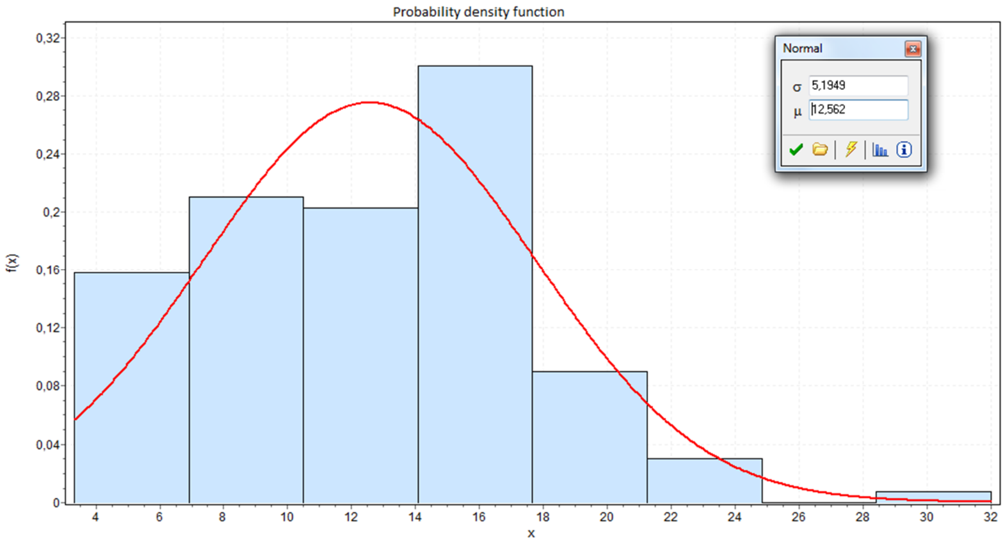


Fig. 5 EasyFit's output for the duration of mixing mortar

Table 1 Probability distribution of the duration of each task

Task	Distribution	Parameters
Carrying concrete blocks	Laplace	$b = 1.7196;\ \mu = 3.2499$
Mixing mortar	Normal	$\sigma = 5.1949;\ \mu = 12.562$
Carrying mortar buckets	Gamma	$\alpha = 23.368;\ \beta = 0.07423;\ \gamma = 0$
Laying concrete blocks	Cauchy	$\sigma = 2.3912;\ \mu = 15.614$

Table 2 Validation of the DES model

Actual duration (min)	Simulation estimate (min)	Accuracy (%)
1060.23	1119.28	94.43

After this process, a set of possible durations is obtained for each task. All sets of data were processed using EasyFit, a software that depicts an efficient approach to carry out goodness of fit tests such as Kolmogorov-Smirnov, Anderson-Darling and Chi-Squared to determine the probability distribution that best fits a sample of data and to provide its parameters, which are required inputs to the DES model considering that the simulation clock will be delayed by the tasks by a random number based on these parameters.

Figure 5 shows an example of the output obtained from EasyFit, the probability density function that best fits the distribution of duration values of the task of mixing mortar. Table 1 shows the probability distribution and parameters, obtained from EasyFit, of the four tasks that form part of the construction activity presented in this work.

4.3.3 Validation of the DES model

A scenario of the DES model was created considering a crew of two workers, one mason and one unskilled labourer, performing the construction activity to complete the total volume of work necessary to complete the project modelled in section 4.2. The scenario was executed for one hundred runs in order to obtain the average estimate of the activity's total duration. This average was compared to the actual duration of the same activity carried out in a similar project during the field observation period.

Similar rules to those stated in section 4.31 were followed by the contractor in charge of the project against which the validation was performed and only the tasks that were modelled for the DES were considering while measuring the actual duration of the construction activity. The number of workers considered in the scenario that was used for validating the model was consistent with those involved in the project carried out by the contractor.

The DES model was assumed valid if it was able to predict the actual duration of the construction activity with an accuracy greater than 80%, a precision degree that has been used in previous studies (Song and AbouRizk 2008, Zayed and Halpin 2004, Osorio Sandoval *et al*. 2016). Table 2 shows the result of the validation of the DES model.

5. Applications

5.1 Studying construction activities

Despite its potential, the use of DES technologies in the construction domain has been mostly restricted to the academic community for research purposes (AbouRizk *et al*. 2011) with limited use in planning and designing construction operations (Kamat and Martinez 2003). Among the reasons for this restriction, the large amount of data required to build a simulation model and its input process, which is time-consuming and error-prone, has been the subject of several research efforts (Lu and Olofsson 2014). To overcome this, a few attempts to integrate DES and BIM technologies have been made (König *et al*. 2012, Lu and Olofsson 2014). These have proved that BIM can facilitate the development of DES models and their subsequent use to evaluate construction performances or alternative designs.

The presented prototype provides an environment to study a single construction activity. It allows users to import their own BIM models and use them to build a DES model that can be used to conduct DES studies involving several modifiable parameters, including the location of the materials in the construction site and the number of human resources performing the tasks in which the activity is divided.

Users can simulate and compare different strategies to execute the construction activity and visualise the results in the human navigable 3D environment provided by the game engine. This may be of great help in decision-making during the preconstruction phase of a project.

Visualising simulations in such way has been proven useful for validation and analysis of simulation models as well as for training emulations and marketing in the context of container logistics (Bijl and Boer 2011) In the field of construction, research in DES is moving towards integration with tools that enhance visualisation (AbouRizk *et al* 2011).

The approach described in this paper can be replicated to model more complex construction activities and expanded to model the interaction of more than one of them.

5.2 Serious game for construction management education

As stated in section 2, this is the first step towards the development of a serious game for construction management education.

In the proposed serious game the player would be able to modify the input parameters of the DES model in a similar way than in the presented prototype. The simulation would run for a given period of time, for example a day, and the player would be able to analyse the performance of the project with the initial parameters, modify them if needed and simulate another period. The DES model would include factors that affect the progress of the project, such as labour absenteeism, rework, weather inclemencies, delays in the procurement process, etc. The goal of the game would be to complete a construction project within time and budget.

Besides acquiring decision making skills, players of this serious game would obtain some knowledge in project integration, time, cost and procurement management, which are some of the key knowledge areas identified in the Guide to the Project Management Body of Knowledge (Project Management Institute 2013). These learning outcomes are aligned with the goal of the game.

6. Conclusions and future work

The presented simulator prototype is a promising approach for integrating DES and BIM models allowing the user to interact with them in a 3D environment. In addition, it allows users to import their own BIM models and conduct their own DES studies, which has many potential uses in industry. Using the BIM model of a facility during the planning of its construction to test different strategies regarding usage of resources, location of materials and hierarchy of tasks may help stakeholders in the decision making process. Moreover, visualising the results of these plans in a 3D environment could also help construction managers to understand their projects faster and better.

Integration of DES and BIM deals with one of the reasons why DES technology is not widely used in industry, namely, the large amount of data required to build a DES model and its error-prone and time-consuming input process. Thus, the presented approach could increase the use of DES technologies in the context of construction management and engineering outside the research community.

Furthermore, the use of a game engine to develop the prototype improves the visualisation of the simulation results, which is of great interest to the community. Researchers could benefit from using the approach to conduct DES studies and present their results to a non-expert audience in a virtual environment that can be easily understood.

The serious game proposed in section 5.2 can be developed using the same approach than that used to develop the presented prototype. However, further work is required to achieve this.

The immediate next step would be to enable the modification of the input parameters of the DES model before the construction activity is completed. This would allow the user to make different decisions as the activity progresses, correcting any deviations from the construction plan.

Secondly, adding some factors that affect the duration of a construction activity to the model. Some examples of these factors may be labour absenteeism, rework, weather inclemencies, delays in the procurement process, etc. This would add some degree of difficulty for the user, who would have to take action when these factors occur in order to complete the activity on time.

Thirdly, modelling the cost of the activity considering parameters other than its duration. For example, if the user has the option of selection better tools to perform a given task it may reduce its duration while increasing its direct cost at the same time. This would force the user to consider the budget and the program of the project simultaneously, which would add even more difficulty for the user and it would resemble real life more closely.

Finally, expanding the model to a whole facility rather than focusing on a single construction activity. This would allow the user to manage a complete construction project considering the interaction between activities.

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