Integration of BIM and Simulation for optimizing productivity and construction Safety

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ABSTRACT: Construction safety is a predominant hindrance in in-situ workflow and considered an unresolved issue. Current methods used for safety optimization and prediction, with limited exceptions, are paper-based, thus error prone, as well as time and cost ineffective. In an attempt to exploit the potential of BIM for safety, the objective of the proposed methodology is to automatically predict hazardous on-site conditions related to the route that the dozers follow during the different phases of the project. For that purpose, safety routes used by construction equipment from an origin to multiple destinations are computed using video cameras and their cycle times are calculated. The cycle times and factors; including weather and light conditions, are considered to be independent and identically distributed random variables (iid); and simulated using the Arena software. The simulation clock is set to 100 to observe the minor changes occurring due to external parameters. The validation of this technology explores the capabilities of BIM combined with simulation for enhancing productivity and improving safety conditions a-priori. Preliminary results of 262 measurements indicate that the proposed methodology has the potential to predict with 87% the location of exclusion zones. Also, the cycle time is estimated with an accuracy of 89%.

Keywords: Construction Safety; Optimization; BIM; Prediction; Productivity.

1. INTRODUCTION

Construction operations' safety is still a predominant and critical issue of the architecture, engineering, and construction industry, the largest industry in the United States [1] and one of the largest in the world accounting for one-tenth of the world's gross domestic product [2]. The accident rate of building industry and the numbers of accidents and deaths are high, leading to a poor reputation of hazardous activities on site [3].

Within the last decade many research studies have addressed the lack of integration of safety improvements with construction. Current representations [4], [5], [6] suggest various approaches to improve workers' safety and integrate it into the construction process.

Recently, the building industry has started to consider using 4D simulation for construction planning; aiming at optimizing performance, by eliminating costs, reducing the expected delivery of the project and most important; increasing the level of safety on-site. The basis for 4D simulation is the integrated application of 3D models [7], [8], [9], construction schedules [10], and associated resources (e.g., material) for early decision-making and project management purposes. Researchers have developed the combination of 4D BIM models with simulation techniques in the past [11]. However, there are still difficulties based on the little interaction between simulation and BIM software that results in time manner constraints for predicting hazardous on-site conditions.

The application of operational research, tracking and estimation via simulation has great capabilities in improving on-site safety conditions. The objective of this study is to explore those capabilities and also to illustrate their interaction with BIM technology in order to promote dynamic modeling for construction safety. By utilizing simulation for on-site traffic management, its application on building information models is examined. The study tries to explore the above by using the Arena software development program to extract time-related data enabling BIM-related scheduling of the workflow; focusing on safety. Weather conditions and light illumination are considered to be iid's. The validation indicates the potential of the proposed methodology to accurately (87%) detect the location of exclusion zones.

2. BACKGROUND

Effective planning is one of the most important aspects of a construction project that influences its overall efficiency while determining its success [12]. Current planning processes in the construction industry are still mainly based on 2D drawings [13], that have been proven to be error prone, and time and cost ineffective when compared with the existing automated methods [14], [10], [15]. On the other hand, model based planning methods (with the help of BIM tools) can improve communication among project stakeholders, help to avoid planning failures and also enable continuous optimization of the construction project [16], [17]. Thus, building models have capabilities to support the project team make wise choices out of a wide range of possibilities.

For the formulation of the construction schedule, planners are required to simulate various construction processes required to build the project [18]. Computer-based decision support tools have provided the construction planner with the ability to plan construction tasks efficiently, but a heavy reliance on these methods could lead to the planning process being seen one-dimensional [19]. Furthermore, BIM tools and applications are now used to enhance on-site safety, design for safety, safety awareness, and enforcement of safety regulations and manage construction safe environments [20], [21].

Since the development of simulation tools, researchers made efforts to relate them with BIM for enhancing project performance, construction design and safety and promote construction process optimization [22], [14], [20]. Others [23], by utilizing BIM, developed a tool that can optimize space allocated to tasks in relation to the critical path schedule. Therefore, hazard space that is generated by an activity can be analyzed using the 4D CAD model. Also, [24] pointed that the 3D or 4D visualization or/and virtual reality are more effectively used for hazard recognition than just the conventional 2D design drawings. The 4D CAD model has been initiated by [5] have initiated the 4D CAD model to assist the hazard identification process.

Those approaches, however promising, required engineers to manually reveal hazards, a task that may require much effort and time. Furthermore, safety information is not really integrated into the 4D CAD model and thus there is no connection between a Building Information Model and safety reports. Additionally, commercial BIM software does not include either applications of simulation for safety, or safety-site management applications that could make the planning process and implementation much easier for engineers and project managers. Finally, it has become a consensus that more attention should be paid to structural safety itself [26] and to conflicts due to inappropriate construction management [27]. Under that viewpoint, BIM and four-dimensional (4D) technology along with simulation tools could be implemented both in research and practice to create safer job-site working conditions.

Given the growing demand for more safety on sites, the fatalities as an effect of the lack of prioritization and the great leap forward that have been made towards the integration of simulation with BIM, the proposed methodology aims at introducing an accurate estimation of exclusion zones (true positive 87%). This can be achieved by the detection of the movement of each dozer from an origin to multiple destinations and vice versa, and the possible maneuvers within each cycle. Using both the illustration of extracted trajectories and the time-space data associated with them, the zones of action can be perfectly defined.

3. METHDOLOGY

The objective of the proposed methodology is focused on two crucial topics; the effective prediction of hazardous on-site conditions related to the routes that are followed from dozers and depended on the phase of the construction, and the exploration of the capabilities of the combination of BIM and simulation for improving safety conditions in advance. For this purpose, the safety routes used by a type of equipment (dozer) from a specific origin point to multiple destinations need to be computed. The most important part is not the computational result and visualization of the trajectories of equipment but the behavior of equipment under different conditions (parameters). As soon as the data are extracted, the computational result can compose the fundamental basis for further analysis and improvement in the field.

The methodology is started with the installation of low cost stereo-cameras in two different and predefined locations on the ground. The base and epipolar geometry between the cameras was every time known. The cameras are mounted such as they can take frames overlapped by 60% in width and 20% in height to permit accurate measurement of the location-over-time of the detecting object. Each of the cameras has recorded 30 frames per second.

Considering the shape and appearance of each dozer, the Semantic Texton Forests (STFs) method is chosen. The shape of a dozer can be decomposed into several basic scheme parts with distinct characteristics (texture and colors). Also the shape of the same dozer varies depending on the view of the camera. Also the appearance of the object varies depending on whether conditions and on-site conditions, inclusive of dust. Another important parameter is the location of each part of the object within the total articulated arrangement.

The extracted video included information regarding the location and moving of 262 dozers from an original point to multiple destinations. In order to train the forecast, we used labeled frames. Each label assigns one pixel. The limitation of this method lies on the fact that for far different sizes of the dozer, the training will be not able to form the characteristics of the detecting object. Therefore, the site is chosen to satisfy the aforementioned limitation and the scale of the detecting object does not change remarkably.

The trained video is then run and the position of the moving dozer is computed. Simultaneously, the time corresponding to its' location per frame is calculated and the project in which the specific dozer is assigned is grouped with the extracting data. The extracting trajectories of the 262 measurements are grouped with information regarding the time-location relationship, the speed per second and the on-site and weather conditions. Also, the cycle time of each dozer is calculated. The grouped data are then simulated with the assumption that the cycle times and weather conditions are independent and identically distributed random variables (iid's).

The simulation is implemented in Arena® software development environment. Arena uses an entity-based, flowcharting methodology, which is efficient in modeling dynamic processes. The main advantage though is the flowchart approach that can be a potential tool for engineers, project managers and designers for documentation of the process. It is also more efficient and easy in validating, verifying and debugging. The highly detailed documents of the process been studied along with the visio-compatible flowcharting tool enables a ultimate tool able to assist all the layer of the construction and project management pyramid. The initial estimators for the cycle time are taken through empirical cycle time data from the Egnatia Motorway Project, in Greece. These data compose the database for further comparison of the actual and simulated data that are based on the time-space related trajectories for Dozers. They also include data for different weather conditions, for different times of a day within 15 consecutive days.

A good independent and identically distributed random variables' (iid) sample is considered to be 10. The simulation clock is set to 100 to observe the minor changes occurred due to external parameters (mud, material loss, suddenly appearing obstacle). The maximum processing time includes all the possible routes i assigned to a destination are presented as G and the different types of the same category of equipment, as for example, a JCB, or CAT dozer are presented as F; set of equipment j. Small differences in the type of the equipment are estimated to have an approximating error of 10% per cycle.

The considered parameters include the origin, destinations, distance, time, field conditions (side impact of weather) and weather. For the purpose of this study we considered only good weather conditions. The parameters that are used for each type are presented below;

1. For the origin of the equipment j we use the parameter arr[j], where j is the set of equipment.
2. For the departure of the equipment j, we use the parameter dep[j].
3. For the different type groups of equipment j, we use the gf[j] parameter.
4. In the case of mud, the largest vehicle j that can be assigned to route i is represented by group[i].
5. The distance between origin i and destination k is dist[i, k] and finally
6. Car[j,r] equals r if equipment is operated by carrier r, 0 if operated by another carrier.

The next step is to define the decision variables. In this level of action, the parameter x[i] equals 1 when a specific type of equipment is used and the value 0 when it is not used. Similarly, parameter j[I,j] takes the value 1 if a specific type of equipment j is assigned for route i; 0 elsewhere. The objective function related to the aforementioned parameters is the minimization of the cumulative function of Xi, meaning $\sum_{i\ to\ G} Xi \rightarrow 0.$ This function is extremely important when we have batches means that are not much correlated, but within the batch, the correlation is strong.

Another important issue is the constraints we need to have for our purpose. There are five levels of constraints that are used for the purpose of our project. These levels are the following:

1. When a specific route i, is assigned to a specific equipment j,

$$(Y[i,j] = 1) \rightarrow X[i] = 1$$

Otherwise, $X[i] = 0$

$$X[i] > Y[i,j]\ \forall\ i\ \in G, j\ \in F \text{ and}$$

$$X[i] < \sum Y[i,j]\ \forall\ i\ \in G.$$

2. Every type of equipment is assigned to one and only route at a specific time space.

$$\sum_{i\ in\ G} Y[i,j] = 1\ \forall\ j\ \in F.$$

3. Each type of equipment must be assigned to a route capable to accommodate the equipment. It is not useful, for example, to consider a wheel track going into high slopes or using a route full covered by mud, since it will probably stack.

$$Y[i,j]F \cdot gf[j] \leq group[i],$$

$$\forall\ i\ \in G, j \in\ F.$$

4. No equipment j arriving earlier in an origin within the site, in order to perform a construction work, than the last "departure" of the previous one m + buffer time, can be assigned simultaneously to the same route I with equipment m.

$$Y[i,j] + Y[i,m] \leq 1,$$

$$\forall\ i\ \in G, j, m \in F | j > m,$$

$$arr[j] \leq dep[m] + buffer\ time$$

5. All routes of the same type of equipment must be assigned to route within a specified distance range. This can be the whole construction site, or a part of it; directly dependable to the management and construction planning.

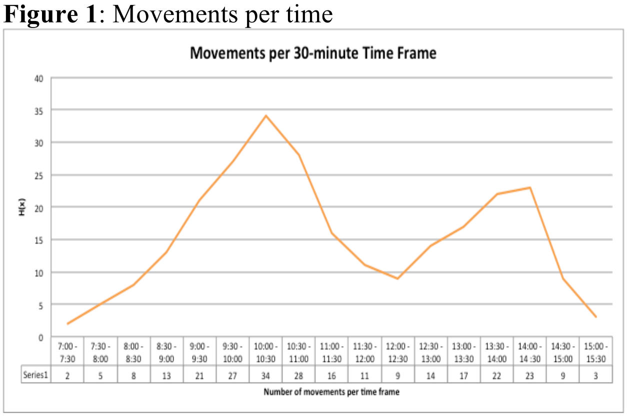
$$Y[i,j] + Y[k,n] \leq 1, \forall\, i,k \in G, and$$

$$j,m \in F, r \in K|K > 1. \text{ Also}$$

$$dist[i,k] \geq \max d, typ[j,r] - typ[m,r] \neq 0$$

The next step is to consider the database of all data that are important for our experimental process. At this point we group the total number of movements per 30 minutes in the time space between 7 am and 3:30 pm (regular working hours in Greece) and created the histogram as illustrated in figure 1.

Figure 1: Movements per time



Based on the histogram, we can observe that there are pick hours especially within the 9am to 11am and 13:00 to 14:30 intervals. These observations are critical for the estimation of the behavior of equipment and the data are collected during 15 consecutive days. From these dates the busiest was the 5th one with 262 movements, since the excavation of the bridge is started. Also the day that matches to the 15th percentile of movements in descending order (85%) was the 8th with 223 movements. The median was in day 3rd with 217 movements.

The dataset input included only the movements with the 8-11am time interval since the number of constraints (432,871) needed a processing time of 5 hours, while the total dataset with more than 1,3 million of constraints had a processing time of more than 25 hours, especially for some scenarios ILOG OPL.

The next step was to extract the origin and destination times for each purpose. As soon as the times are observed, all successive movements with identical type numbers are matched. Based on three major criteria; the existence of previous or following movement from the same origin, equipment left the origin and the equipment that arrives to the origin; a set of arrival-departure from a specific point is computed. Table 1 represents the minimum number of routes required for each measurement during the 100%, 85% and mean. Also, a comparison between the scheduled and actual number of routes within a day are presented. The distances of 600, 400 and 200 meters are considered as well.

4. RESULTS

The overall results are presented below:

1. The required number of routes increases by the demand for equipment

2. The route assignment for the actual times requires a higher number of routes that the scheduled, even for lower traffic. The reason is that the actual time that equipment occupies a route is higher than the scheduled time.

3. In all cases, an increase in buffer time increases the demand for routes

4. For buffer times less than 5 minutes, the optimal solution is not affected by any distance constraint

5. When the maximum allowed distance is greater than 400 meters the optimal solution is not affected by the distance constraint

6. For buffer times greater than 15 minutes, the maximum allowed distance to less than 200 meters result to a major increase of the optimal solution, therefore, the problem becomes infeasible.

The results presented above compose the fundamental basis for further improvement in the combined field of simulation, BIM and safety. When the database with the cycle times assigned to the routes, the estimated time for these operations can be observed and both the operation and construction cost is reduced. Simultaneously, the safety level can be increased since the extracted trajectories can be used to estimate the maximum (at least optimal) space needed for such operations in-situ. Therefore, the optimized solution composes the milestone in the combination of these data with the minimum requirements of Construction Safety Regulations can help managers organize the site and establish exclusion zones properly.

In order to measure the performance of the proposed methodology in detecting the location of exclusion zones, both precision and recall are used. Precision is calculated as TP/(TP+FP) that corresponds to the number of correctly recognized locations divided by the number of recognized locations. A high detection precision implies a high accuracy in detecting actual location of exclusion zones. Low detection precision means a high number of wrong detected exclusion zones. Recall is calculated as the TP/(TP+FN) and the product corresponds to the number of correctly recognized exclusion locations to the total area of locations. According the result, the detection completeness can be evaluated.

In order to calculate the precision and recall ratios of the detection of exclusion zones in a construction site, the actual exclusion zones of the same site zone are detected, according to the safety regulations. Then, the proposed methodology detected the location of exclusion zones by using the reduction to absurdity. As it is done in mathematical solutions, the location of exclusion zones equals the area excluded from the area that encloses the action radius of a dozer; as it is define by the trajectory of the moving object. This way, the number; thus the percentage, of correctly recognized locations of exclusion zones (TP), the number of recognized locations (TP+FP) along with the number of actual locations of exclusion zones (TP+FN) in each frame are retrieved. Based on the aforementioned calculations the detection precision and recall can be calculated.

Table 1. The minimum number of routes required for each measurement for the 100%, 85% and mean for different buffer times.

		MAXIMUM ROUTE DISTANCE								
		no constr	600	400	200		no constr	600	400	200
BUFFER TIME		busiest day, scheduled time					busiest day, actual time			
	0 min	16	16	16	17		15	15	15	18
	5 min	19	19	19	20		19	20	20	19
	10 min	23	23	23	25		23	24	22	23
	15 min	27	28	INFEASIBLE	INFEASIBLE		27	27	26	26
	20 min	INFEASIBLE	INFEASIBLE	INFEASIBLE	INFEASIBLE		INFEASIBLE	INFEASIBLE	INFEASIBLE	INFEASIBLE
		85% day, scheduled time					85% day actual time			
	0 min	14	14	14	15		14	14	15	15
	5 min	17	17	18	18		18	18	19	19
	10 min	20	20	21	22		21	21	22	22
	15 min	23	23	23	25		24	23	24	24
	20 min	26	28	INFEASIBLE	INFEASIBLE		26	29	29	INFEASIBLE
		average day, scheduled time					average day, actual time			
	0 min	14	14	15	15		13	14	14	14
	5 min	17	17	17	18		17	18	17	17
	10 min	21	21	21	22		21	21	21	21
	15 min	26	26	27	INFEASIBLE		21	23	23	24
	20 min	27	27	27	INFEASIBLE		27	28	28	INFEASIBLE

The method of getting the detection and recall followed the test of the images. The results of decision and recall are shown in the following Table 2. As it is shown in table 2, the average precision of the proposed methodology in detecting the location of exclusion zones equals the 87%. Also, the average detection recall is 84.5% with a range from 50 to 100% for the parameters that used in the experiment. As it can also be observed, both the precision and recall are lower during the morning and the late afternoon hours. This reflects the effect of illumination and the existence of humidity that causes blurriness and alters the color and the accurate detection of the dozer. Moreover, during noon, the sunrays drop vertically and the existence of shadow is eliminated. The same applies to the rays reflected from the earth to the sun.

Table 2. Precision and Recall in the detection of exclusion zones for the different times of the day.

Time of the day	Precision (%)	Recall (%)
Early Morning	84.2	80.1
Midday	87	84.5
Afternoon	82.6	79.2

Another important issue is the cycle time. The cycle time is calculated using the arena software and equals the average cycle time of a dozer moving from one origin to a specific destination. The actual measurements of the total time a dozer needed to go from an origin to the destination point is first extracted from the trajectory of the vehicle in real time. Then the total cycle time is simulated under different scenarios, as they discussed above. According to the performance of the simulation, the cycle time is estimated with an average accuracy of 89% with a range from 80 to 98%. It is important to consider that the total number of time related data are approaching the normal distribution; therefore, the total number of measurements based on an error of 1.0 for a 95% level of confidence is sufficient.

As the result of the above, both the project manager and the constructor manager can be benefitted from the existence of the proposed methodology because more accurate estimations and thus plans on a daily basis can be made. Moreover, the productivity can be increased since a more accurate estimation of the cycle time can be estimated, and also the time-money loss can gradually decrease. Last and foremost, the number of accidents will decrease and also the location of dangerous zones can be observed.

5. CONCLUSIONS

The pre-existing practice in safety optimization and predictions is not able to resolve the major issue of construction safety. The reason is summarized in the lacking of implementation of technology in predicting and optimizing safety, therefore the falsification of the results is of high probability and also cost and time increase exponentially to the database set. In an attempt to take advantage of the capability of BIM in including safety regulations and data, as an example, exclusion zones, the project proposes a novel methodology for simulating the flows of dozers; as the most common type of equipment, to understand their behavior and add value on safety management.

The novel methodology combines the state-of-the-art in automatic image based detection, tracking and simulation with the Building Information Modeling to analyze the flow of dozers within the construction site (from an origin to multiple destinations). The results provide us with an accurate estimation of the dangerous maneuvers and promote the exploration of the capabilities of BIM combined with simulation for enhancing and increase safety in-situ. The proposed methodology is implemented in Arena® software development environment. The results indicated the location of exclusion zone with an accuracy of 87%, while the estimation of the cycle time reached the 89% of accuracy.

The results presented above compose the fundamental basis for further improvement in the combined field of simulation, BIM and safety. As soon as the estimated operational time for a specific route assignment is observed, the behavior of the dozer under different scenarios is observed and the dynamic (in time manner) trajectories enable dynamic scheduling and also prediction of possible unsafe conditions under the tested scenarios.

These data can be also enriched with several parameters. Further assessment shall include information about a variety of weather conditions and a variety of equipment to retrieve more information from images/videos and simulation. Moreover, the growing demand for more reliable data related to construction safety may yield to a milestone where the safety regulations may require these assessments in the project management level. Also the location of exclusion zones can be analyzed dynamically for the different phases of a construction related project based on the capabilities of BIM.

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