5th International/11th Construction Specialty Conference
5e International/11e Conférence spécialisée sur la construction

Vancouver, British Columbia
June 8 to June 10, 2015 / *8 juin au 10 juin 2015*

AN INTEGRATED FRAMEWORK TO PREVENT UNSAFE PROXIMITY HAZARDS IN CONSTRUCTION BY OPTIMIZING SPATIO-TEMPORAL CONSTRAINTS

N. Roofigari Esfahan[1,4], J. Wang[2] and S. Razavi[3]
[1] PhD Candidate, Dept. Of Civil Engineering, McMaster University, 1280, Main West, Hamilton, Canada
[2] PhD Candidate, Dept. Of Civil Engineering, McMaster University, 1280, Main West, Hamilton, Canada
[3] Assistant Professor, Dept. Of Civil Engineering, McMaster University, 1280, Main West, Hamilton, Canada
[4] corresponding_author_roofign@mcmaster.ca

Abstract: Hazardous proximity of construction resources, such as construction equipment, materials, and workers-on-foot has been identified as a distinct safety issue on construction jobsites. Spatial and temporal limits are practical constraints that coexist in movement of construction resources. Space and time conflicts could substantially hinder the productivity of ongoing activities as well as causing safety issues. Therefore, the spatial and temporal constraints and the state of construction resources need to be considered to prevent space-time conflicts and unsafe proximities. The state of a moving construction resource includes its position, moving direction/heading, speed, orientation, and other safety-related information. The area around each resource is divided into alert and warning areas which are quantified for them according to their corresponding spatial or proximity constraints. By integrating the states of resources, their warning/alert areas, and proximity constraints, as well as by visualizing them in time-integrated 2D space, a more precise understanding of potential hazardous situations can be achieved and therefore prevented. This paper presents a visual support tool aiming to reduce safety hazards in project planning stage by optimizing spatio-temporal proximities of resources. For this purpose, the developed method first optimizes potential movements of the resources by minimizing intersection of their warning areas and avoiding overlap of their alert areas. Thereafter, it visualizes the optimized locations of resources in time-integrated 2D space throughout the duration of their corresponding activities. In this way, the integrated visualization framework enables managers to make more judicious decisions and take corrective actions pertinent to safety hazards prevention. A numerical example with different scenarios and proximity measures is analyzed to test and validate the proposed framework.

Key Words: Construction Safety; Spatio-Temporal Constraints; Optimization; Alert and Warning Areas; Visualization

1 INTRODUCTION

Construction sites are generally comprised of multiple resources such as personnel, equipment, and materials moving in pre-defined spaces. These resources are involved in dynamic work tasks which require moving through space at different times on the job site. Because of their frequent unstructured and almost random motion, these resources can come in close proximity to each other. If not coordinated and organized properly through optimized work planning (schedule and resource leveling), spatial interference can lead to incidents between two or more resources (personnel, equipment, material). These incidents can be characterized as contact collisions that can threaten the safety and health of construction personnel (Teizer et al., 2010).

Mustafa and Al-Bahar (Mustafa and Al-Bahar, 1991a) have identified risks sources central to construction activities to be physical, environmental, design and logistics based risks. Also the most frequent causes of accidental death and injuries were found to be falls, falling materials and collapses, as well as mobile resources' accidents. Such risks can be reduced if the use of vehicles and mobile resources are properly managed. As a result, proper routing of resources can affect the cost and the time during construction projects by reducing safety risks. in addition, major productivity gains in terms of the reduction in wastage and working time can be achieved by planning the site from a logistics perspective (Mahdjoubi and Yang, 2001). Accordingly, during a construction project, site planners need to select paths for site operatives and vehicles. Such path planning in construction site spaces is a complex and multi-disciplinary task as it involves accounting for a wide range of scenarios and conditions. In other words, provision of safe paths could be used to control high-risk situations on the site and helps in having safe and efficient working conditions(Soltani et al., 2002).

Consequently, path/trajectory planning aids to improve safety and productivity margins by providing time-optimal and collision-free paths for navigating through the construction site that seek to prevent hazardous contacts between construction elements. To identify the potential of unsafe contacts between construction elements, it is essential to understand the potential regions of intensive activities not only during execution, but also in the planning phase. This definitely helps in having a more efficient activity resource planning which also increases safety on the job site. However, despite its importance, path/trajectory planning is not efficiently taken into account in the planning stage of construction projects. Further, although there are methods tending to optimize motion paths of resources or robots for special site operations (e.g. (Bernold, 1993, Olearczyk et al., 2010, Lee and Adams, 2004), still the time factor is very much neglected in both analysis and visualization. These methods mainly use shortest path algorithms such as Dijkstra to find 2D trajectories for construction resources. A common problem of current studies is that the distance between entities is the only factor taken into consideration and the direction of the entities's movements (headings) are neglected. In some cases, the distance between two entities could be flagged and alarmed as an unsafe proximity while in reality, the entities are moving apart from each other.

To fill the gap in the literature, this paper aims at optimizing trajectories of construction resources in time-integrated 2D space in planning phase of the project. For this purpose, this study proposes and develops an unsafe proximity avoidance model focused on decreasing resources interactions throughout the planned activities' duration. The model uses the attributes of distance and moving direction to define state of different resources and predict and optimize their motion through space and time. Subsequently, this paper discusses the key factors that should be considered in quantitatively defining the distance thresholds between resources. Current research either has not fully considered these factors, or has not described the relationship between the distance threshold and these essential factors (IHSA 2013; Marks and Teizer 2013). The thorough description of the proposed method is presented in following sections.

2 RELEVANT LITERATURE

Unsafe proximity of workers-on-foot to construction equipment or equipment-to-equipment has been identified as one of the distinct safety issues on construction jobsites (Pradhananga and Teizer 2012). Struck-by hazards are the second leading cause of construction fatalities, in which approximately 58% fatalities are resulted from struck-by-equipment (Wu et al. 2013). Thus, entities on construction jobsite have to interact and co-ordinate effectively with each other to maintain a safe environment. Even though such issue has been extensively studied in previous research efforts, the published casualty statistics indicate that contact collisions remain a major problem in construction industry. Hence, the trajectories of construction resources should be properly planned and monitored so that the potential collisions can be prevented in a timely manner. The trajectory of a construction entity includes the information regarding its movement in space and time, taking into account its position, moving direction/heading, speed, orientation, and other safety-related information.

Optimizing trajectories of resources and operations is a common practice in different industries. Specially, trajectory optimization methods are widely used for planning optimal trajectories of robotic systems and machineries (Posa et al., 2014, Ahmad et al., 2013, Betts, 1998). With the growing use of robots and automated systems in construction industry, the problem of trajectory planning of these systems has been raised. Previous work on trajectory and path planning analysis in construction focused on three principal categories: (1) navigation of multiple vehicles, (2) efficient jobsite geometric modeling, and (3) real-time motion planning and control of equipment (Cheng et al., 2012). These methods are either focused on the trajectory planning of robotic workers, or equipment used in special construction processes. The early works in this regard included simulated work studies focused on large vehicle routing around an industrial construction site (Varghese and O'Connor 1995), motion planning for automated construction excavation (Bernold, 1993), heavy lift planning (Lin and Haas 1996), interactive path planning for vehicle operations (Tserng et al. 2000), and visualization of construction simulation (Kamat and Martinez, 2001).

In order to execute the construction activities in a safe and efficient manner, construction site spaces needs to be properly planned. The risky sources of construction activities were identified to be physical, environmental, design, logistics, financial, legal, political, and operational risks(Mustafa and Al-Bahar, 1991b)). As a result, the paths of construction resources need to be planned in a way to be associated with less risks and would not cause congestion on the construction site. In addition, routing of resources affects the cost and the time during construction projects, and major productivity gains in terms of the reduction in working time can be achieved. Soltani et al. (Soltani et al., 2002, Soltani and Fernando, 2004) presented the application of path planning on construction sites according to multiple objectives. In their method, they evaluated the performance of three optimisation algorithms namely: Dijkstra, A∗, and Genetic algorithms. The optimised path in this approach was defined as the shortest path, the safest path, the most visible path or a path that reflected a combination of short distance, low risk and high visibility. Chi et al. (2008) examined crash avoidance algorithms for providing routes that prevent collisions with other movable objects on a construction site. While the calculated path avoided crashes, it was not necessarily the most efficient. Other methods used the highly parallel unconstrained Dijkstra approach in order to develop a new optimal algorithm in which paths were subjected to turning constraints such that the final solved path contained no turns greater than 45°((Solka et al., 1995, Hassoun, 1990). In this regard, Pei et al. (2009) also generated a basis for vehicle movement trajectory reconstruction in two-dimension collision accidents and accidents disposal. Recently, some methods also focused on providing potential optimized paths for special construction equipment or operations, e.g. (Filla, 2013, Lin et al., 2014, Wi Sung et al., 2012). Lin et al. (2014) performed motion planning for mobile construction machinery to generate collision-free path for multiple construction machines, including wheel-type, track-type and chain-type machines, moving simultaneously on a construction site, based on the true movement of construction machinery. (Wi Sung et al., 2012) also introduced a Genetic Algorithm-based Repetitive Tasks Simulation (GARTS) model for planning steel erection in high-rise building construction. This model produced an optimized movement path of a bolting robot for fabricating steel structures, proposed a collaboration plan between a robot and a worker, and quantified the uncertainty of the duration of steel erection.

Visual representation of the stated resource paths is the next step towards efficient planning of construction sites. In other words, visualizing simulated construction operations can provide valuable insight into the subtleties of construction operations that are otherwise non-quantifiable and presentable. This is because planners must comply with many considerations, such as increasing construction productivity, decreasing site congestion and providing a safe work environment during the process of site space planning which is more achievable when properly visualized (Zhou et al., 2009). (Kamat and Martinez, 2001) presented the Dynamic Construction Visualizer, which enabled spatially and chronologically accurate 3D visualization of modeled construction operations and the resulting products. William et al. (2007) also developed a dynamic path planning system to improve mobile robot navigation in a dynamic building construction site by integrating a set of sensor-equipped robots into a real-time indoor positioning system, using the ultra wide band (UWB) position system. The method then displayed the mobile robot movements and paths in a 3D CAD drawing in a real-time manner.

As stated, when dealing with heavy machinery and vehicles, following a safe and efficient path reduces the risk of worker injury and fatality, reduces collateral damage to equipment, and improves overall work efficiency. However, limited research in path finding on construction site has been conducted. In addition, although the 2D or 3D visualization of these paths has many potential uses toward the monitoring and maintenance of an automated construction site, still all the few available visual methods disregard the time aspect of the possible congestions when planning and visualizing the paths of actual resources. Up to now, such trajectories in construction industry are only available recently for unmanned Aerial Vehicles (UAVs) (Alejo et al., 2014) or for workers-on-foot (Dagan and Isaac, 2015). Their innovative method presented a new system for assembly and structure construction with multiple Unmanned Aerial Vehicles (UAVs) which automatically identifies conflicts among them. After detecting conflicts between UAVs, the system resolved them cooperatively using a collision-free 4D trajectory planning algorithm based on a simple one-at-a-time strategy to quickly compute a feasible but non-optimal initial solution. Further, the available methods still do not take into account the results of the interaction between two individual workers with different characteristics, which might create safety risks and their daily interactions with other site equipment and obstacles. As a result, the method presented in this paper tends to fill the gap in the current literature by proposing a time integrated framework for trajectory optimization of construction resources, aiming at preventing the proximity hazards in the construction job sites. The detailed description of the optimization method follows.

3 TRAJECTORY OPTIMIZATION-VISUALIZATION FRAMEWORK

As stated in previous sections, visualizing simulated construction operations in time-integrated 2D space can provide valuable insight into the subtleties of construction operations that are otherwise non-quantifiable and presentable. The optimization method presented in this paper aims at generating minimized-congestion trajectories for construction resources. This is done in two essential inter-related phases, namely trajectory optimization and visualization phases, as shown in Figure 1. This framework consequently enables spatially and chronologically accurate visualization of modeled construction operations and the resulting optimum planned trajectories for activity resources. This section describes the steps of the time-integrated 2D trajectory optimization-visualization framework.

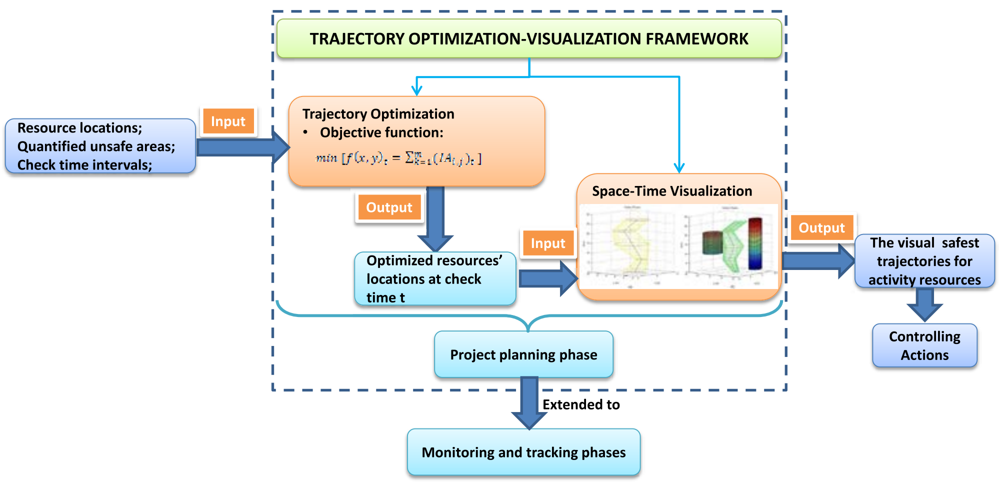

Figure 1: Trajectory optimization-visualization framework

The optimization method presented in this paper uses the unsafe proximity detection process presented by (Wang and Razavi, 2015). In this method, the authors divided the area around equipment into alert and warning areas. Further, the distance threshold used for unsafe proximity identification is differently considered when the piece of equipment is moving as opposed to staying stationary. The key factors that should be considered in quantitatively defining such distance thresholds are then described. This approach will prevent congestions between activity resources in the planning phase, which will subsequently lead to achieving more safety and higher productivity rates from the resources.

3.1 Quantification of Alert and Warning Distances

In this study, alert area is defined as the hazardous area around the equipment, and warning area is the area that has the potential to become hazardous under certain conditions. A hazard refers to a situation that an entity is within the alert area. For the proof of concept, circles are adopted as an approximation of the alert and warning areas for equipment and workers-on-foot (Figure 2). It should be noted that different equipment exhibits different alert distance (R1) and warning distance (R2). Accurately quantifying R1 and R2 can assist in effectively performing proximity detection methods and also contributes to enhancing mobility and productivity on the job site.

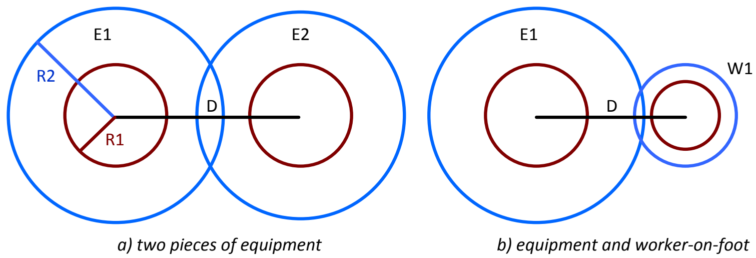

Figure 2: Intersection between warning areas of a) two pieces of equipment and b) equipment-worker

For one piece of specific equipment, alert distance R1 is the same under general condition, regardless of its static or moving state. This study uses forklift as sample equipment to explain the process of defining R1 and R2. It is expected that no intersection of alert areas occurs when the forklift comes to a complete stop. This study adopts 2 meters as the alert distance for the forklift with 2.5 tonne capacity. The determined 2 meters includes the length of the fork attached to the forklift. In order to take into account all conditions, including both congested and non-congested time periods, this paper proposes adjusting warning distances for the same equipment over time. The warning distance for equipment is adjusted by considering equipment reaction distance and equipment braking distance. Equipment reaction distance is the distance that equipment travels after the operator’s realization of a hazard and before a determined response (e.g. brake) exactly comes into work. Equipment braking distance is defined as the distance the equipment will travel from the point when its brakes are fully applied to the point when it comes to a complete stop. As thus, R2 needs to be increased when the equipment is moving with a higher speed. Likewise, for the equipment with a lower speed, this distance is decreased in order to have efficient space allocation on the job site.

For workers-on-foot, an alert area with an average 1 meter diameter is adopted which is the area a worker demands for safety operation of different construction activities (Dagan and Isaac, 2015). An average 1.5 meters is adopted as the warning distance. The difference between the warning distance and the alert distance is 1 meter which is the distance a worker needs to achieve a complete stop upon realizing a hazard occurrence. It is obtained by multiplying the mean of actual comfortable gait speed of men at 30s and 40s (Bohannon, 1997) and the average reaction time of a normal people (Technology Associates, 2014).

3.2 Trajectory Optimization

This paper proposes a step-by-step optimization algorithm to find the safest trajectory for activity resources in the planning phase, based on the information available in this phase of the project. For this purpose, first, a set of check time intervals is defined based on the nature of the project. These check time intervals are then used to attain the optimum average location of each activity resource as shown in Table 1. It should be noted that, the step-by-step nature of the algorithm enables it to be applicable to planning as well as monitoring and tracking phases; i.e. when exact location and progress at one time is known, and the planned trajectory needs to be re-optimized to plan for following movements in space and time. The developed safety planning method was applied in MATLAB. Its application is carried out in the following steps.

3.2.1 Identification of resource locations and their safety areas

For construction equipment and workers-on-foot, safety area refers to their warning area and alert area. For temporary or permanent site facilities and obstacles, safety area refers to the area around them that other construction resources (static or dynamic) are not allowed to be inside except by authorizations. To start the optimization process, the approximate coordinates of the expected location of each resource is determined based on the nature and the schedule of activities they will be involved in. The alert distance (R1) and warning distance (R2) are also to be defined at each time. Subsequently, the step-by-step optimization is initiated. The process of defining R1 and R2 starts at the first check-time, which is generally the start of the project or the date on with a certain part of the project starts for which a safe trajectory needs to be planned. In each check-time, the alert and warning areas are created around the approximate planned location as shown in Figure 2. The location optimization will only take place in predefined check-time intervals. Therefore, whenever equipment is added or removed, its starting point will be added and then its optimization will start from the first nearest check time and then the whole trajectory will be demonstrated through space and time in the visualization phase.

3.2.2 Location optimization

The purpose of this phase is to minimize the potential hazardous contacts between resources that co-exist in each check-time. First, the distance between each two different resources (D) and the intersection of their safety areas need to be calculated. It should be noted that, the method is able to take into account not only hazardous contacts between resources, but also the possible contacts between these resources and any temporary or permanent site facilities and obstacles. Distance D is then defined as the center-to-center distance of the warning areas of two resources or a resource and an obstacle that is calculated using Equation 1; where (x_i, y_i) and (x_j, y_j) are the approximate coordinates of resource i and j, respectively, at check time t.

[1] $$D = \sqrt{[x_i(t) - x_j(t)]^2 + [y_i(t) - y_j(t)]^2}$$

When calculating the intersection between safety areas of each two resources, three possible situations might exist:

1. Distance D is greater than the summation of the warring areas of the two resources, in which no intersection area (IA) between safety areas would exist.

[2] $$D \geq R2_i + R2_j \rightarrow IA = 0$$

2. Distance D is less than the subtraction of the warring areas of the two resources, in which intersection area is the area of the smaller warning area of the two.

[3] $$D \leq R2_i - R2_j \ , R2_j \leq R2_i \rightarrow IA = \pi R2_j^2$$

3. Distance D is greater than the subtraction of the warring areas of the two resources, and less than their summation. This means the areas are partially overlapped. In such case intersection area is calculated as follows:

[4] $$R2_i - R2_j \leq D \leq R2_i + R2_j \ , \rightarrow$$

[5] $$IA = R2_j^2 \cos^{-1}\left(\frac{D^2 + R2_j^2 - R2_i^2}{2D R2_j}\right) + R2_i^2 \cos^{-1}\left(\frac{D^2 + R2_i^2 - R2_j^2}{2D R2_i}\right) - \frac{1}{2}\sqrt{(-D + R2_j + R2_i)(D + R2_j - R2_i)(D - R2_j + R2_i)(D + R2_j + R2_i)}$$

This paper focuses on the third case in which a partial overlap between safety areas occurs. Therefore, the objective is to minimize the total intersection areas of all resources that co-exist in each check time t

(Equation 6). In this optimization process, the coordinates of each resource at time t is set as decision variables. As a result, the optimization process seeks for the optimum coordinates for each resource that will minimize the total intersection areas considering the rules and constraints of the project. It should be noted that no overlap can be existed between two resources' alert areas. In other words, no entity would be allowed to enter the alert area of the other entity. This condition is employed as a constraint to the optimization process as shown in Equation 7.

[6] $min\ [f(x,y)_t = \sum_{k=1}^{m}(IA_{i,j})_t\ ]$

Where: $m = C_2^{n_t} = \frac{n_t!}{2 \times (n_t - 2)!}$ $, n = number\ of\ resources\ at\ time\ t$

[7] $D \geq R1_i + R1_j$

The optimization process is performed for all check-times. Consequently, vectors of the optimum trajectories for all the resources in time-integrated 2D space are created. The achieved optimum trajectories as well as the prisms are then realized in the visualization phase to give the planners a better sense of the safety hazards and the optimum trajectories. Based on the obtained plan, in the project implementation phase, the rates at which planned activities are expected to be carried out, and the rate achieved from the optimum trajectory can be compared to ensure optimality of the assessed productivities. Therefore, this method represents resources' movements, and also verifies that they adhere to the planned productivities at all times.

3.3 Space-time trajectory visualization

In the presented study, time–space diagrams were developed to represent the actual movements of resources along different paths on the construction site. The time–integrated 2D space diagrams, whose (x,y) axis represent the changing locations of resources on site and the vertical axis represents time, were developed as prisms representing the locations of resources as well as potential safe spaces available to them on the site at different time (Figure 3). The time-integrated 2D space diagrams are used to visualize the movements of resources and to ensure their safety through planning the safest distance between their prisms. Each optimum trajectory is simultaneously represented as a number of polylines in the diagram, connecting the optimum locations at each time interval to the next. Space distance between resources, introduced in time order to reduce safety risks, is represented as distances between the polylines.

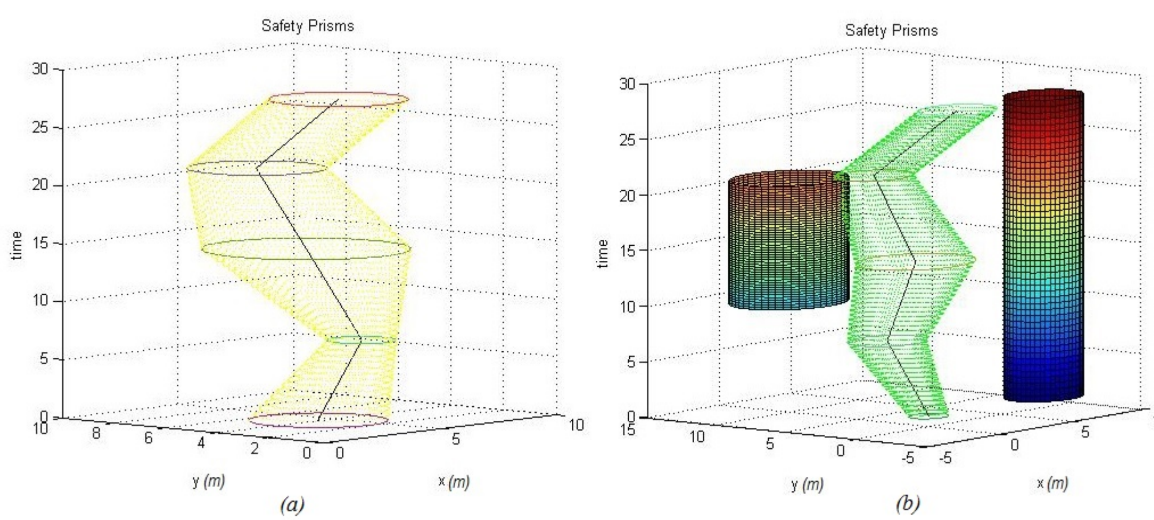

Figure 3: Realization of prism for one activity a) without and b) with site obstacles

As stated earlier, in addition to the representations of the movements of equipment and workers on the site, certain static objects (i.e. temporary or permanent site facilities and obstacles) and areas on the site that may expose resources to hazards are also represented in the space-time diagram. For example, some of the workers may need to work at a certain distance from a crane, or from a storage area with flammable material. Such elements are represented as cylinders in the diagram. The footprint of the shape represents the portion of the site occupied by the object, and its height represents the duration for which the object remains on the site as shown in figure 3b. Figure 3a demonstrates the prism for equipment as well as the optimum trajectory throughout its execution period. Figure 3b illustrates the result of the optimization process when one piece of equipment is to perform, and one temporary and one permanent obstacle exist on the job site. Figure 4 demonstrates the intersection between resources with site obstacles as well as between two activities with different start and finish times in time-integrated 2D space. Table 1 and Figure 5 respectively represent the initial data inputs and visualization of a small sub project including three resources (equipment 1, 2 and 3). As shown in table 1 and figure 5, check time intervals of 7 days are considered in this example. However, for equipment 3 that starts at day 5 from start of the sub-project, its optimization starts on day 7, i.e. at the nearest pre-defined check time interval.

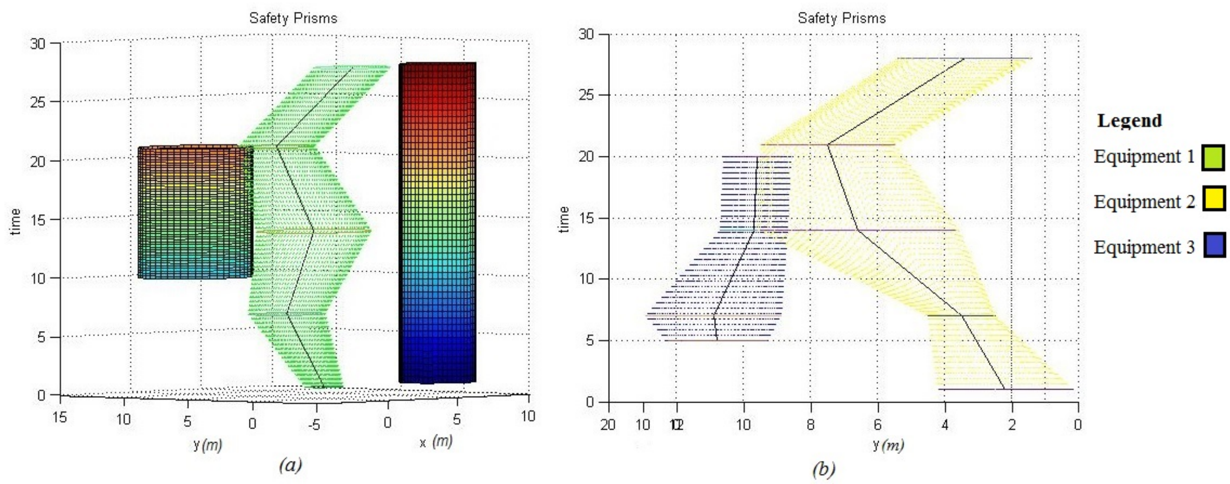

Figure 4: Realization of 2D intersections between a) activity and site obstacles and b) two activities

Table 1: Data inputs of three resources

Resource	Time	X coordinate	Y coordinate	Warning distance	Alert distance
Equipment 1	1	0	0	10	2
	7	1	4	11	2
	14	2	3	14	2
	21	3	7	11	2
	28	2	0	11	2
Equipment 2	1	2	2	11	2
	7	5	3	9	2
	14	6	6	11	2
	21	5	7	13	2
	28	4	3	11	2
Equipment 3	5	8	10	9	2
	7	9	10	11	2
	14	7	9	9	2
	20	6	9	8	2

- Once the resources' movements on site have been analyzed, the construction managers can implement controlling actions and approve of a safe construction plan. In cases in which the planned or actual distance between resources is not acceptable as a result of a special site condition, or the planned productivities deviate from the planned, the following actions can be taken:

- Adjustment of the planned schedule, in order to move the resource space-time prisms in time by changing the timing of the activities they are to be carried out, or stopping it for some time in between and re-continuing when the space issue is resolved.
- Adjustment of the way in which a planned activity will be carried out (for example, by allocating different equipment to a worker), in order to reduce the risks identified in the first stage of the application of the model, and consequently the safety distance that needs to be kept between the resources can be maintained.

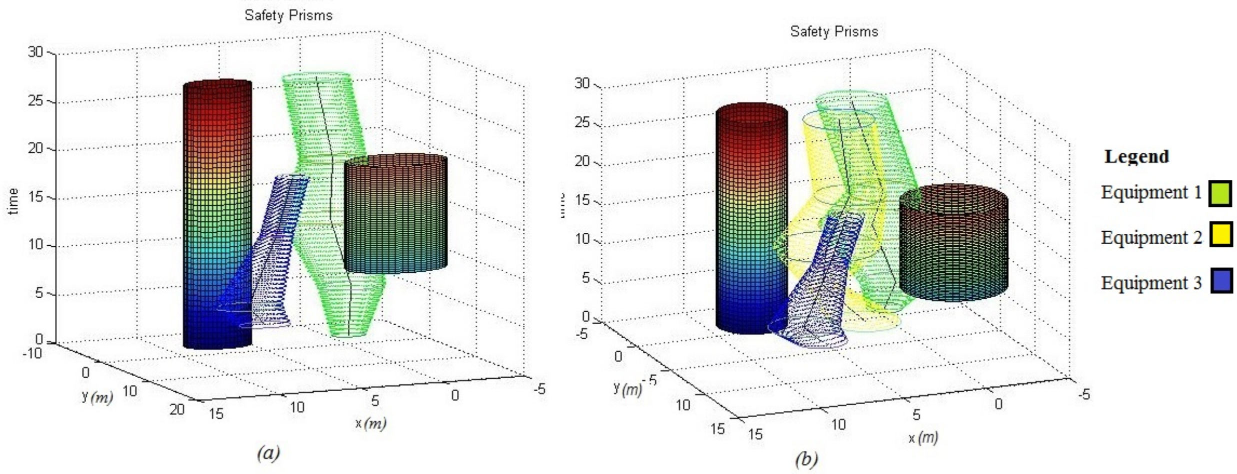

Figure 5: Realization of the optimum space-time prisms for a) two and b) three activities

4 CONCLUSION

A methodology has been developed for analyzing and if necessary adjusting the planned locations of construction resources on sites, in order to prevent the hazards that occur due to an excessive proximity between different resources. Such hazards may occur due to the impact that the resources of an activity have on the safety of other resources carrying out other activities in adjacent locations on the site. This research focuses on the minimizing the intersection between safety areas considered for each resource, in a way to both prevent site congestions and unnecessary space allocations, since this problem has not been sufficiently studied so far.

The proposed methodology includes a step-by-step optimization method for the assessment of distances between resources, and the use of prisms to analyze the existing construction plan. These tools allow managers to take into account the dynamic activities of the resources on sites, as well as the different characteristics of different resource types which may reinforce or counteract risk factors. The proposed method can be particularly useful for projects in which activities are repetitive, reducing the complexity of resources' movements and increasing their predictability. By utilizing other shapes to represent the safety areas around equipment and site elements, such as using a rectangle for a permanent building on the job site, to further improve the effectiveness of the model is the future step of this study.

References

Ahmad, R., Tichadou, S. & Hascoet, J. Y. 2013. 3d safe and Intelligent Trajectory Generation for Multi-axis Machine Tools Using Machine Vision. *International Journal of Computer Integrated Manufacturing,* 26**,** 365-85.

Alejo, D., Cobano, J. A., Heredia, G. & Ollero, A. 2014. Collision-Free 4D Trajectory Planning in Unmanned Aerial Vehicles for Assembly and Structure Construction. *Journal of Intelligent & Robotic Systems,* 73**,** 783-95.

Bernold, L. 1993. Motion and Path Control for Robotic Excavation. *Journal of Aerospace Engineering,* 6**,** 1-18.
Betts, J. T. 1998. Survey of Numerical Methods for Trajectory Optimization. *Journal of Guidance, Control, and Dynamics,* 21**,** 193-207.
Cheng, T., Mantripragada, U., Teizer, J. & VelaA, P. 2012. Automated Trajectory and Path Planning Analysis Based on Ultra Wideband Data. *Journal of Computing in Civil Engineering,* 26**,** 151-160.
Dagan, D. & Isaac, S. 2015. Planning safe distances between workers on construction sites. *Automation in Construction,* 50**,** 64-71.
Filla, R. Optimizing the trajectory of a wheel loader working in short loading cycles. 13th Scandinavian International Conference on Fluid Power; June 3-5; 2013; , 2013 Linköping; Sweden. Linköping University Electronic Press; Linköpings universitet, 307-317.
Hassoun, M. H. Fast computation of optimal paths in two- and higher dimension maps. Circuits and Systems, 1990., IEEE International Symposium on, 1-3 May 1990 1990. 710-713 vol.1.
Kamat, V. & Martinez, J. 2001. Visualizing Simulated Construction Operations in 3D. *Journal of Computing in Civil Engineering,* 15**,** 329-337.
Lee, S. & Adams, T. M. 2004. Spatial model for path planning of multiple mobile construction robots. *Computer-Aided Civil and Infrastructure Engineering,* 19**,** 231-45.
Lin, J., Hung, W. & Kang, S. 2014. Motion Planning and Coordination for Mobile Construction Machinery. *Journal of Computing in Civil Engineering,* in press**,** 04014082.
Mahjoubi, L. & Yang, J. L. 2001. An intelligent material routing system on complex construction site. *Logistics Information Management,* 14**,** 337-43.
Mustafa, M. A. & Al-Bahar, J. F. 1991a. Project risk assessment using the analytic hierarchy process. *IEEE Transactions on Engineering Management,* 38**,** 46, 48-50.
Mustafa, M. A. & Al-Bahar, J. F. 1991b. Project risk assessment using the analytic hierarchy process. *Engineering Management, IEEE Transactions on,* 38**,** 46-52.
Olearczyk, J., Hermann, U., Al-Hussein, M. & Bouferguene, A. 2010. Spatial Trajectory Analysis for Cranes Operations on Construction Sites. *Construction Research Congress 2010.*
Posa, M., Cantu, C. & Tedrake, R. 2014. A direct method for trajectory optimization of rigid bodies through contact. *Int. J. Rob. Res.,* 33**,** 69-81.
Solka, J. L., Perry, J. C., Poellinger, B. R. & Rogers, G. W. 1995. Fast computation of optimal paths using a parallel Dijkstra algorithm with embedded constraints. *Neurocomputing,* 8**,** 195-212.
Soltani, A. R. & Fernando, T. 2004. A fuzzy based multi-objective path planning of construction sites. *Automation in Construction,* 13**,** 717-34.
Soltani, A. R., Tawfik, H., Goulermas, J. Y. & Fernando, T. 2002. Path planning in construction sites: performance evaluation of the Dijkstra, A*, and GA search algorithms. *Advanced Engineering Informatics,* 16**,** 291-303.
Teizer, J., Allread, B. S., Fullerton, C. E. & Hinze, J. 2010. Autonomous pro-active real-time construction worker and equipment operator proximity safety alert system. *Automation in Construction,* 19**,** 630-640.
Wang, J. & Razavi, S. 2015. Low False Alarm Rate Model for Unsafe-Proximity Detection in Construction. *Journal of Computing in Civil Engineering,* in press-Published online on 8 January 2015**,** 04015005.
Wi-Sung, Y., Hak-Ju, L., Dong-In, K., Kyung-IN, K. & Hunhee, C. 2012. Genetic algorithm-based steel erection planning model for a construction automation system. *Automation in Construction,* 24**,** 30-9.
Zhou, F., Abourizk, S. M. & Al-Battaineh, H. 2009. Optimisation of construction site layout using a hybrid simulation-based system. *Simulation Modelling Practice and Theory,* 17**,** 348-63.