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# Planning safe distances between workers on construction sites

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ABSTRACT

A planning methodology is introduced to ensure that workers on construction sites remain at a safe distance from each other. The methodology is based on the assumption that hazardous conditions, which occur on sites due to the proximity of different workers, depend on the interaction between both reinforcing and counteracting characteristics of the workers. The methodology includes a matrix-based method for the definition of minimum safe distances between workers, and the use of 3D time–space diagrams to represent and analyze the dynamic movements of workers on site. The methodology is implemented in a real case study in order to verify its feasibility.


## 1. Introduction

According to conservative estimates, at least 60,000 people are fatally injured on building sites around the world every year [7]. Many hundreds of thousands more suffer serious injuries and ill-health. Worldwide, construction workers are three times more likely to be killed and twice as likely to be injured as workers in other occupations [3]. While fatal work injuries in the private construction sector in the US increased by 5 percent in 2012, this followed five consecutive years of declining fatal injury counts [14]. In the UK, the number of worker deaths in 2012/13 was 18% lower than the average for the past five years [6]. Although the statistics may show some improvement, they also clearly indicate that safety on construction sites remains a major problem.

Workers on construction sites are exposed to hazards that have three main sources: a) the work technology (e.g. the tools and equipment used to carry out the activity), b) the physical conditions (e.g. high elevations) and c) surrounding activities that are simultaneously carried out by other workers nearby [13]. This research focuses on the prevention of hazards of the third type: i.e. those created by surrounding activities. While there are many methods and models available to assess the risks that workers' own activities pose to themselves, few studies have dealt with the hazards derived from the activities of other workers on site to which workers are also frequently exposed [24].

The problem of accidents on construction sites that are caused by an excessive proximity between workers carrying out different activities is exacerbated by the fact that construction sites are dynamic: the location of workers is transient, and the physical structure and activities often change. Such accidents could be prevented by carefully planning and monitoring the location of workers on site while they perform activities, so that they can maintain a safe distance from other workers or their equipment at all times. However, in order to achieve this one needs to establish how such safe distances should be defined in the first place. Furthermore, one needs to provide managers with the tools to plan the construction activities accordingly. These tools should take into account the fact that both workers and equipment frequently change location.

The objective of this research is to develop a methodology that supports planning the dynamic locations of workers on construction sites, in order to prevent hazards that occur due to an excessive proximity between different workers. This paper will continue in Section 2 with a review of existing models and previous research. The third section presents the methodology that was developed in this research, and describes its application. Section 4 presents the results of an implementation of the methodology in a real-life case study, which was carried out to evaluate its feasibility.

## 2. Literature review

### 2.1. General construction safety planning tools and models

A significant number of studies have been carried out to develop tools and models for the planning of safe construction sites. Rozenfeld et al. [16] developed a Construction Job Safety Analysis tool, which focused on the identification of potential loss of-control events for a detailed planning of construction activities, based on data collected through interviews. Mitropoulos et al. [13] presented a model of the factors affecting the likelihood of accidents during a construction activity. The model focuses on the characteristics of a project that generate hazardous situations and shape actual work behaviors, and analyzes the conditions that trigger the release of the hazards. Saurin et al. [19] defined a Safety Planning and Control Model that includes three

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hierarchical levels, for long-, medium-, and short-term safety planning. Proactive and reactive performance indicators were defined for safety control and evaluation, based on the percentage of safe work packages and actual accident data. Jannadi and Almishari [8] developed a risk assessor model for determining the risk associated with a particular activity and the justification factor for a proposed response action. Tam et al. [21] developed a Non-Structural Fuzzy Decision Support System to evaluate safety management systems and prioritize safety improvement measures with the consideration of various decisions. Yi and Langford [24] analyzed historical safety records, and presented a model for estimating the risk distribution of a project and adjusting the project schedule to reduce risk. Hadikusumo and Rowlinson [4] developed a design-for-safety-process tool, aimed at capturing safety knowledge from safety engineers about construction safety hazards and the safety measures required.

These tools and models can provide valuable general information for safety planning, through the analysis of the causes of accidents and historical data. They are, however, neither sufficient for fully analyzing the likely locations and timings of accidents on a specific site, nor can they take into account the results of the interaction between two individual workers with different characteristics, which might create safety risks.

### *2.2. General work space allocation tools and models*

A number of models have been developed for the allocation of the space required for activities on construction sites. Some of these models also take into account safety hazards. Riley and Sanvido [15] developed a manual space planning method that provided a logical order and priority for space planning decisions. The model allowed planners to identify potential spatial conflicts. Shaked and Warszawski [20] developed a knowledge-based expert system for work space allocation, which differentiates between horizontal zones (floors) and vertical zones (elevator shafts, staircases, piping shafts, and exterior facades). Akinci et al. [1] developed a model for automatically detecting conflicts between activities in four dimensions, categorizing these conflicts according to a taxonomy of time–space conflicts, and prioritizing the spatial conflicts detected. Winch and North [23] developed a decision support tool for marking up available space on site, allocating activities to spaces, and analyzing and optimizing space allocation in relation to the critical path.

While all these tools and models address the need to allocate site space for activities according to the specific conditions and schedule of the project, they do not fully address safety considerations by taking into account the characteristics of individual workers. Moreover, most of these models (the pioneering study by Riley and Sanvido [15] is a notable exception) focus on the definition of a static space for the execution of each specific task, which usually surrounds the component constructed in this task. Thus, they do not fully take into account the workers' movements on the site, (e.g. for fetching materials and removing waste).

### *2.3. 4D safety planning systems*

A number of safety planning systems have been developed that take into account the spatial location of activities on site. Benjaoran and Bhokha [2] developed an integrated system for construction and safety management, which includes a 4D CAD model and a rule-based system that automates the hazard identification process. The rule-based system also suggests proper safety measures, including safety activities or requirements. Sacks et al. [18] developed a method for generating a set of possible loss-of-control scenarios for each planned activity in a given project, based on the likely locations of workers. A set of algorithms is then used to compute the probability of potential victims to be exposed to the loss-of-control scenarios. Zhang et al. [25] developed a rule-based safety checking system for the automatic identification of hazards that appear as the building is constructed, identifying their location in a Building Information Model, and providing solutions to mitigate the hazards. The proposed framework was implemented for the prevention of falling-from-heights accidents. Kang et al. [11] linked a 4D model with risk data to visualize the risks in each activity. Their system considers construction cost, duration and safety as risk factors.

All these systems take into account the spatial location of activities on the site to enhance worker safety. However, they do not deal directly with planning the location of workers on the site to ensure that safe distances are kept between different workers, as the present research does.

## 3. The proposed methodology

The objective of this research is to define a methodology that can reduce the hazardous conditions that occur on construction sites due to an excessive proximity between different workers. This study focuses on the proximity between workers, in addition to their proximity to equipment or dangerous materials on site, since workers often carry out their work in a dynamic and complex way that is difficult to model. Furthermore, this problem has not been sufficiently addressed in previous research.

This research is based on the assumption that hazardous conditions, which occur on sites due to the proximity of two workers carrying out different activities, are a product of the interaction between both reinforcing and counteracting characteristics of the workers. Such characteristics affect the probability that an accident will occur, and depend both on the activity carried out by a worker, as well as on the worker's individual attributes. For example, the risk of a welder accidentally causing a fire that injures another worker also depends on the degree of flammability of the materials used by the other worker, such as oil or paint. In other words, the level of risk depends not only on the severity of the hazard created by a reinforcing characteristic of one worker, but also on the degree to which a characteristic of the second worker counteracts this hazard. The implication of this is that not all workers need to be kept at the same distance from the area in which a certain activity is being carried out.

Prior to the application of the methodology, a preliminary stage involves an analysis of the planned processes on the site and the identification of the risks involved. After this preliminary stage, the model is applied in two stages:

1. Definition of required minimum distances between workers, using a matrix-based tool
2. Analyzing the planned movements of workers on site, using 3D time–space diagrams.

After the model is applied, the manager can implement controlling actions and approve a safe construction plan (Fig. 1).

### *3.1. Process analysis and risk identification*

The preliminary stage of the application of the model involves a structured Preliminary Hazard Analysis (PHA) of the planned processes on site, which is followed by a detailed Job Safety Analysis (JSA) to identify the risks that are involved in specific activities within these processes. In line with the research objective, both PHA and JSA are focused on the hazards and risks to which workers are exposed because of surrounding activities. The input for this stage includes the existing construction plan for the project, which includes the scheduled activities.

The objective of the PHA is to identify the hazards that might be created by the processes that are planned to be carried out on site. The PHA involves a systematic survey of all the processes in the existing construction plan, and of the activities, resources and site space that these processes require, to identify the hazards that they might consequently involve.

A more detailed JSA is then carried out of those activities for which hazards were identified in the PHA. The JSA is carried out by breaking the activity down into a sequence of individual steps that are simple, continuous and clearly identifiable. The JSA provides decision-makers

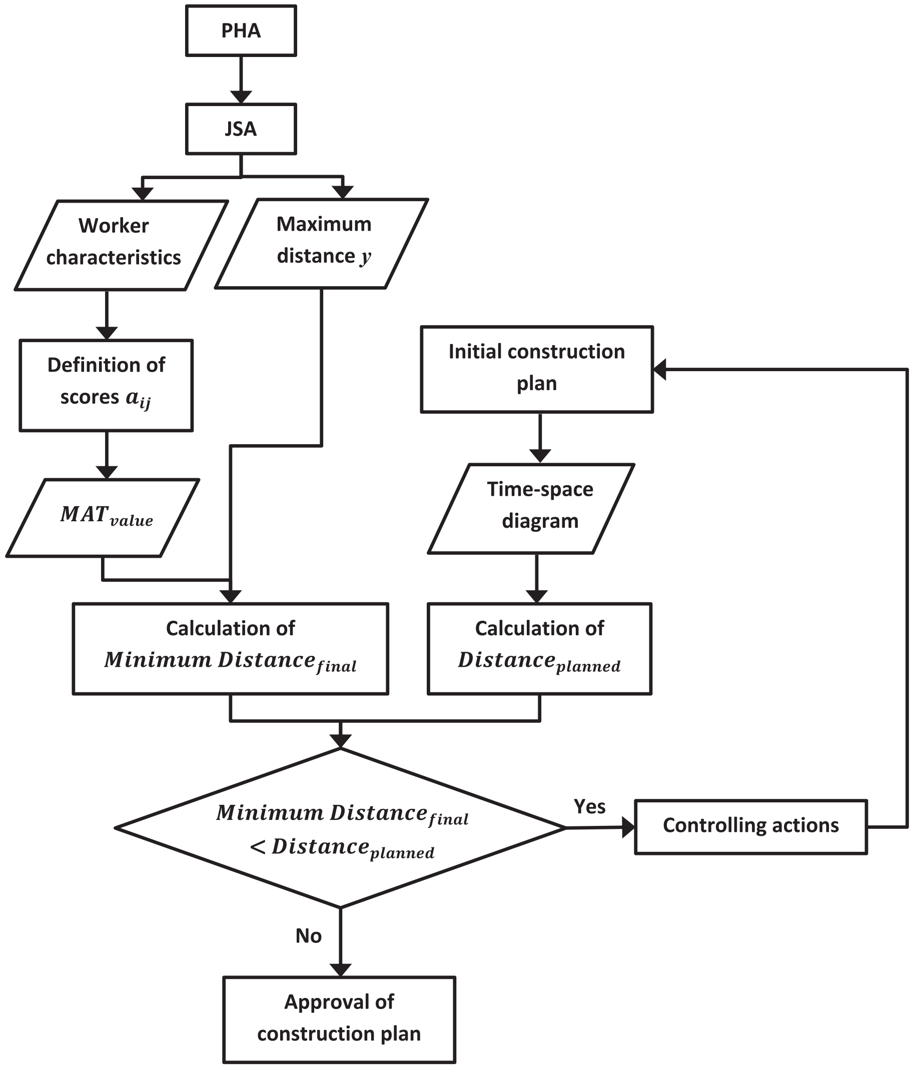


**Fig. 1.** Application of the methodology.

with two outputs that serve the next stages of the implementation of the methodology, as will be explained in the following sections:

- The characteristics of the workers on site that may affect the existence of the hazardous conditions identified in the JSA.
- The distance that has to be kept between two workers on the site under conditions of maximum risk, as defined by the hazardous conditions that may occur while activities are carried out.

### *3.2. Development of a matrix-based tool for definition of safe distances*

Following the initial stage of risk identification, the characteristics of each worker on the site are analyzed in order to define the required minimum distances between pairs of individual workers that carry out different activities. Characteristics that may affect the existence of the previously identified hazardous conditions are addressed. As explained above, it is assumed that the hazardous conditions are a product of the interaction between reinforcing and counteracting characteristics of the workers, and that a hazard created by a reinforcing characteristic of one worker may be counteracted by a characteristic of the second worker. Consequently, pairs of characteristics are defined for each worker, so that a characteristic of one worker interacts with a different characteristic of another worker. A reinforcing characteristic of worker A could be for example the use of equipment that might injure a worker B. A counteracting characteristic could be the level of worker B's protective equipment, or his training and experience in working in proximity to that equipment, which can reduce to a certain extent the risk of an accident. The analysis of these different interacting characteristics of pairs of workers facilitates the calculation of the distance at which they may affect each other, and the consequent minimum distance that must be kept between them in order to prevent accidents.

Once the workers' reinforcing and counteracting characteristics are identified, each characteristic of a worker is given a score on a 1–5 point Likert scale by a safety manager. The types of characteristics that are identified for the different workers are identical, but the characteristics of each specific worker are given individual scores. These scores represent the relative level at which a characteristic may cause the specific worker to affect or to be affected by a hazardous condition in his immediate surroundings (1 point representing a minimum level and 5 a maximum level). The scores for each worker's characteristics are defined by the safety manager in a matrix, containing *j* pairs of reinforcing and counteracting characteristics that have been identified:

$$[A] = \begin{bmatrix} a_{11} & a_{21} \\ a_{12} & a_{22} \\ \vdots & \vdots \\ a_{1j} & a_{2j} \end{bmatrix}, \tag{1}$$

where $a_{ij}$ is the score given for characteristic *i* out of *j* pairs of characteristics of worker *A*.

Each pair of characteristics contains one reinforcing and one counteracting characteristic that are related to a specific hazard, such as the risk of electrocution or fire-related burns. When two workers are in proximity to each other, the level of risk will depend on the interaction between two characteristics – the reinforcing characteristic of one worker and the corresponding counteracting characteristic the second worker, which is related to the same hazardous condition. These characteristics are defined for each individual worker in equally sized matrices (since the types of characteristics are identical):

$$[A] = \begin{bmatrix} a_{11} & a_{21} \\ a_{12} & a_{22} \\ \vdots & \vdots \\ a_{1j} & a_{2j} \end{bmatrix}, [B] = \begin{bmatrix} b_{21} & b_{22} & b_{23} & \dots & b_{2j} \\ b_{11} & b_{12} & b_{13} & \dots & b_{1j} \end{bmatrix}. \tag{2}$$

The matrix defined for worker *B* mirrors that of worker *A*. For example, reinforcing characteristic $a_{11}$ of worker *A* interacts with counteracting characteristic $b_{21}$ of worker *B*, while counteracting characteristic $a_{21}$ of worker *A* interacts with reinforcing characteristic $b_{11}$ of worker *B*. The level of risk for two specific workers carrying out activities in proximity depends on the interaction between their individual characteristics. In order to calculate the minimum distance that needs to be maintained between these two workers, so that the risks to which they are exposed can be reduced, the matrices in which their characteristics have been defined are multiplied:

$$MAT = [A] \cdot [B] \tag{3}$$

$$MAT_{value} = \left(a_{11}b_{21} + a_{21}b_{11} + \cdots + a_{2j}b_{1j}\right) \tag{4}$$

where $MAT_{value}$ is defined as the sum of all the entries of the matrix product *MAT*. By multiplying the scores, a relatively large weight is given to those instances in which both the reinforcing and counteracting characteristic are given a high score (indicating a high level of exposure to the hazardous condition). The lowest possible value of 2*j* for $MAT_{Value}$ is obtained when all the characteristics of both workers are given the minimum score of 1. In such a case, it is assumed that no distance has to be kept between the workers:

$$MAT(min)_{value} = 2j \Rightarrow f\left(MAT(min)_{value}\right) = 0 \tag{5}$$

The highest value of 50*j* for $MAT_{Value}$ is obtained when all the characteristics of both workers are given the maximum score of 5. In such a case a distance *y*, which has been defined for conditions of maximum risk, has to be kept between them:

$$MAT(max)_{value} = 50j \Rightarrow f\left(MAT(max)_{value}\right) = y \tag{6}$$

The definition of distance *y* is based on the JSA carried out in the previous stage.

Any value in between the two extremes of 2*j* and 50*j* that is obtained for $MAT_{value}$ can be converted into an initial minimum distance that would be required between two specific workers, lying somewhere in between 0 and *y*, through the following function (Fig. 2):

$$Minimum\ \ Distance_{initial} = f(MAT_{value}) = \frac{y}{48j} MAT_{value} - \frac{y}{24} \tag{7}$$

While a linear function was used here to define the minimum required distance, other non-linear functions could be used in the model as well. In addition, different weights can be defined for the interaction of different characteristics, to reflect their relative importance.

In addition to the representation of the characteristics of individual workers in matrices, the existence of particular conditions on the site, such as the simultaneous presence of workers belonging to different

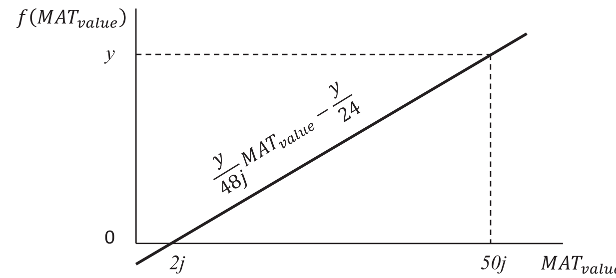


**Fig. 2.** Calculating the minimum distance between two elements.

subcontractors, are represented through binary coefficients $C_l$. These coefficients represent the existence of *l* particular conditions on the site that could aggravate or alleviate hazardous conditions, and which would therefore require a relative increase or decrease in *Minimum Distance$_{initial}$*. In order to identify the actual distance required between two workers, the initial distance is multiplied by the coefficients $C_l$:

$$Minimum\ \ Distance_{final} = \prod_{l=1}^{n} C_l f(MAT_{value}) \tag{8}$$

### *3.3. Development of a safety planning method, based on time–space diagrams*

Following the definition of minimum distances between different workers in order to ensure their safety, there is a need to analyze their movements on site, according to the activities previously defined in an existing construction plan. Based on this plan, the rates at which planned activities are expected to be carried out, and the movement paths of workers on the site can be assessed. A method is required to represent these movements, and verify that they adhere to the minimum distances at all times. 3D *time–space diagrams*, whose (x,y) axis represent the changing locations of workers on site, while the vertical axis represents time, were developed in this research to represent as a polygonal chain (or polyline) the location of a worker on the site at different points of time (Fig. 3). The proposed method can be particularly useful for projects in which activities are repetitive, reducing the complexity of workers' movements and increasing their predictability. Hence, the development of these diagrams was inspired by linear scheduling diagrams.

Linear scheduling (also called line-of-balance, time-location or location-based scheduling) is a visual technique that uses lines in diagram to represent the activities carried out at specific locations on a site [10,17]. In these diagrams, the points on one axis represent repetitive physical sections of the building being constructed, such as zones, floors, or apartments. The second axis represents time, so that the section of the building in which an activity is carried out at any moment can be identified in the diagram (Fig. 4). One of the main principles of linear scheduling is synchronization: planning the schedule so that different sequential activities are executed at similar production rates. A synchronized linear schedule can be identified by parallel lines that show a constant time buffer between these sequential activities.

In the present study, a time–space diagram was developed to represent the actual movement of workers along different paths on the construction site, rather than their general location in a number of repetitive sections of a building. In this, the diagrams are more similar to those sometimes used to plan linear infrastructure projects, such as roads or railways. However, the linear scheduling diagrams used in infrastructure projects only represent activities that are carried out along a single path on the site (although possibly in different directions on this path). They can therefore enable the planning of time buffers between workers moving along the same path, but not the planning of space buffers between workers moving along different paths on the site

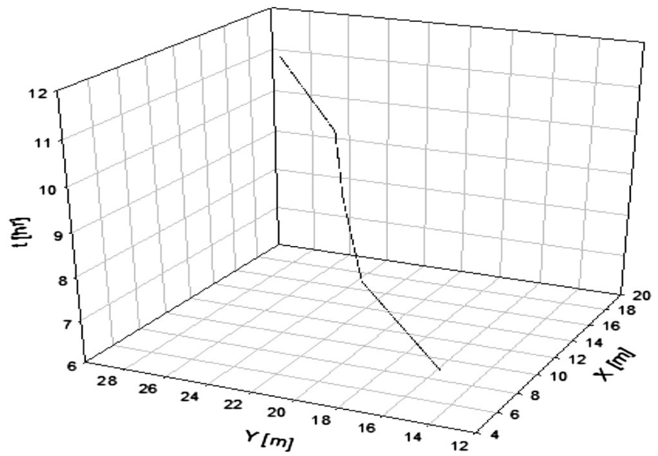


**Fig. 3.** Time–space diagram representing the location of a worker on site at different points of time.

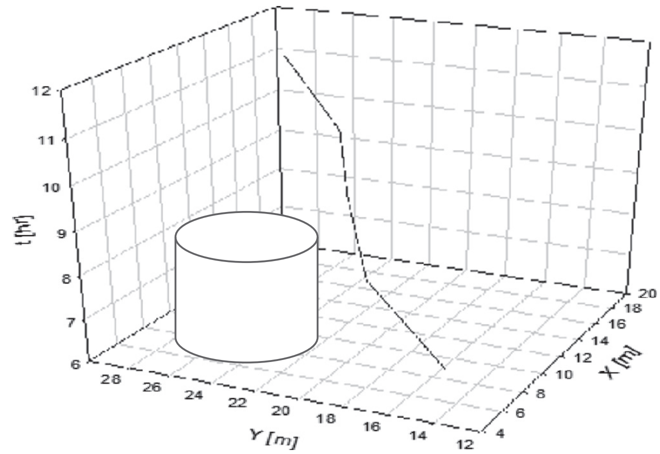


**Fig. 5.** Time–space diagram representing a movement path and a static object.

Moreover, since linear scheduling diagrams represent repetitive physical sections of the site such as the floors of the building being constructed, the separation of workers can only be based on those sections. The present research on the other hand assumes that the required distances between workers depend on the interaction of individual reinforcing and counteracting characteristics of the workers and their activities. Therefore, the definition of a single predetermined "work envelope" around an activity isn't always appropriate for safety planning: while some workers can be allowed to working in proximity, others need to be kept far apart. The safety plan is therefore based on the movements of workers according to the exact coordinates of their locations on site, as represented in the time–space diagram.

The 3D time–space diagram is used to analyze the movement of workers along different paths on the site, and ensure their safety through the planning of required space buffers between the workers. Multiple paths are simultaneously represented as a number of polylines in the diagram. Space buffers between workers, introduced in order to reduce safety risks, are represented as distances between the polylines. In addition to the representation of the movement of workers on the site, certain static objects and areas on the site that may expose workers to hazards are also represented in the time–space diagram. Minimal distances between those objects and the workers can then be assured. 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 objects are represented in the diagram as 3-dimensional shapes (Fig. 5). 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. A space buffer can thus be planned between the object and specific workers that are simultaneously working on the site, as a distance between the edges of the shape representing the object, and the polyline representing the movement of the worker.

The safety planning method was applied in MATLAB. Its application is carried out in the following steps:

1. Assessment of the rates at which planned activities are expected to be carried out, and of the workers' movement paths on the site, according to the existing construction plan.
2. Representation as a polyline in the time–space diagram of the location of each worker $i$ on the site, as a function of time $t : [x_i(t), y_i(t)]$.
3. For each pair of workers $i$ and $j$, calculation of the planned distance $Distance_{planned}$ between the workers at time $t$, as the linear distance between the workers' locations $[x_i(t), y_i(t)]$ and $[x_j(t), y_j(t)]$ on the polylines representing their movements:

$$Distance_{planned}(t) = \sqrt{\left[x_i(t) - x_j(t)\right]^2 + \left[y_i(t) - y_j(t)\right]^2} \quad (9)$$

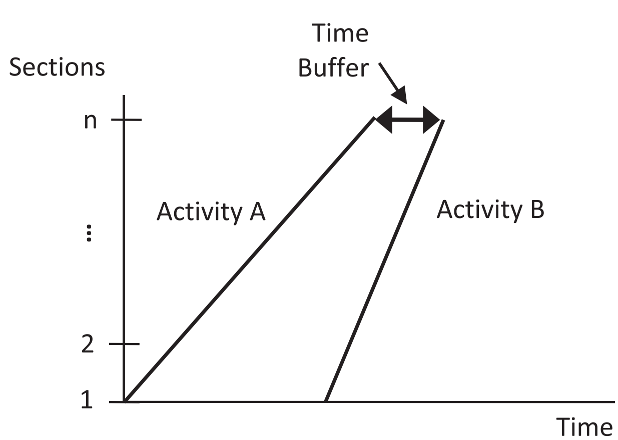


**Fig. 4.** Linear scheduling diagram.

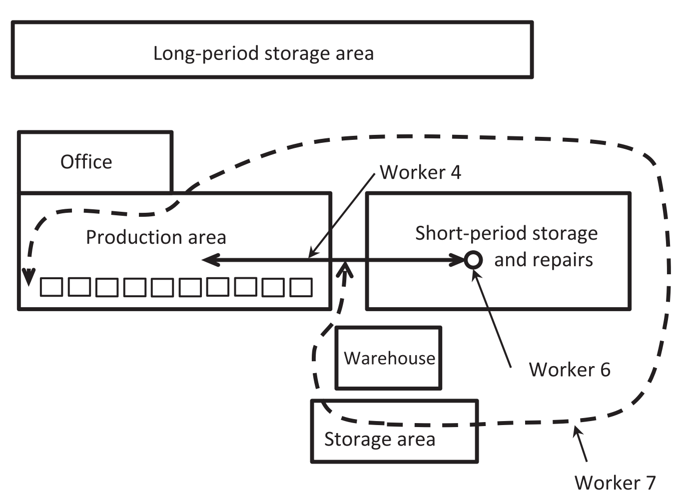


**Fig. 6.** Plan of the production plant that was the subject of the case study.

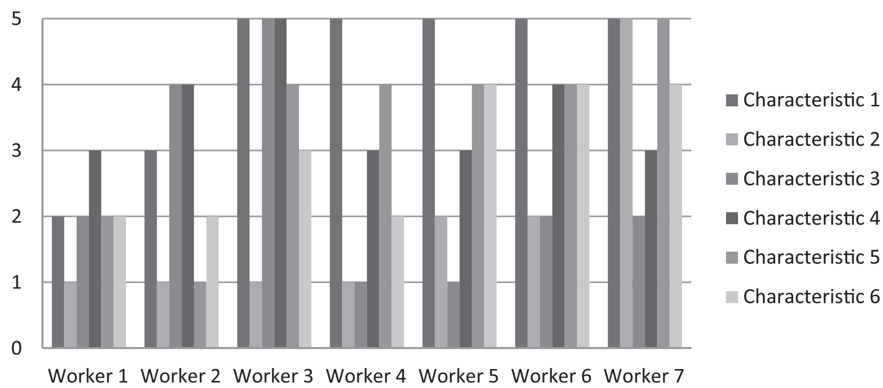


**Fig. 7.** Scores for the characteristics of seven different workers.

4. Identification of instances in which the planned distance is less than the previously defined minimum safe distance:

$$Distance_{planned}(t) = < Minimum\ \ Distance_{final}. \tag{10}$$

### 3.4. Controlling actions and approval of a safe construction plan

Once the workers' movements on site have been analyzed, the construction manager can implement controlling actions and approve a safe construction plan. In those cases in which the planned or actual distance between workers is less than the minimum safe distance, the following actions can be taken:

- Adjustment of the planned schedule, in order to separate the workers by changing the timing of the activities they carry out.
- 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 distance that needs to be kept between the workers.

In the present research these controlling actions are assumed to be manually defined. It would be possible to automatically adjust the activities in the schedule according to the required distances between workers once a mathematical model is developed that can describe worker movements on the site. This indicates the need for research in developing such a model, which would support the definition of the required start and finish times of activities in light of the required distances between workers. A precedent for such a research can be found in [5].

In the present research controlling actions are assumed to be carried out proactively, when the planned distance between workers is found to be less than the minimum safe distance. But controlling actions could also be carried out real-time, when the actual distance is less than the required distance due to deviations from the plan. Real-time control would naturally require an appropriate automated tracking system. A number of studies have demonstrated that readily available and relatively inexpensive real-time location technologies can be used to identify the precise locations of workers on construction sites [22,9,12]. In case the locations of workers are monitored during the execution of the project, instances can be identified in which the actual distance between workers at time $t$ is less than the minimum safe distance:

$$Distance_{actual}(t) < Minimum\ \ Distance_{final}. \tag{11}$$

## 4. Implementation of the methodology

In order to establish the feasibility of the methodology, it was implemented in a real case study of a production plant for the prefabrication of large reinforced concrete elements, such as walls, beams and ceiling panels (Fig. 6). The plant was used as a site for implementing the methodology, since the activities carried out there are repetitive, and this allowed the results of the implementation to be replicated and verified. Moreover, similarities were observed with the work typically carried out on large construction sites, in terms of the types of activities that were carried out (e.g. concrete pouring and the welding of reinforcement), and the materials and equipment used (e.g. cranes and forklifts moved on site alongside workers on foot). In addition, different subcontractors were simultaneously working on the site, as is the case in most construction sites.

The initial stage of the implementation of the methodology was an extensive PHA and JSA. The process chosen for further analysis in a JSA was the prefabrication of reinforced concrete exterior walls with a stone panel cladding. In the JSA, this process was broken down into nine activities, and hazards were identified for each activity.

In the second stage of the implementation, scores were given for the characteristics of seven different workers: two production workers, a welder, a crane operator, an assistant to the crane operator, a worker carrying out finishing works and a forklift operator. Three pairs of characteristics were scored to test the model (Fig. 7). For each reinforcing characteristic (such as the capability to cause fire-related injuries) a corresponding counteracting characteristic was defined (such as the level of protection from fire):

1. The capability of injuring other workers with the equipment used in the activity
2. The worker's experience in carrying out the activity
3. The capability to cause other workers fire-related burns
4. The worker's level of protection from fire
5. The number of safety events in the worker's record
6. The safety training that the worker had undergone.

For each characteristic, explicit criteria were defined to determine the appropriate score, through consultation with a focus group that

**Table 1**
Minimum required distances between workers (cm).

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | | | 60 | **Worker 2** |
| | | | | 140 | 110 | **Worker 3** |
| | | | 110 | 70 | 60 | **Worker 4** |
| | | 100 | 200 | 80 | 60 | **Worker 5** |
| | 150 | 130 | 200 | 100 | 90 | **Worker 6** |
| 240 | 230 | 170 | 240 | 140 | 100 | **Worker 7** |
| **Worker 6** | **Worker 5** | **Worker 4** | **Worker 3** | **Worker 2** | **Worker 1** | |

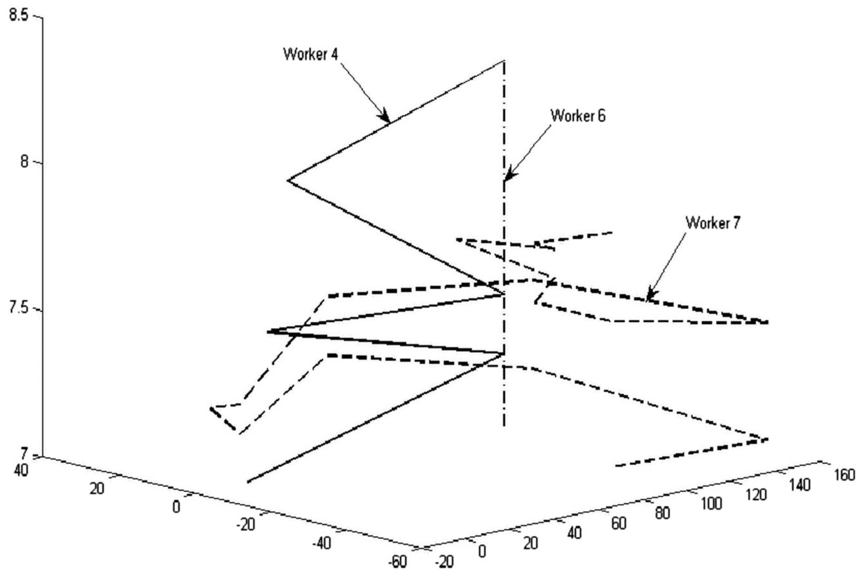


**Fig. 8.** Time–space diagram representing the different paths.

included the operations manager of the plant, the production manager, the safety consultant and a mechanical engineer. For example, for the second criteria, a worker with less than half a year's experience received a score of 5 points, while a worker with more than 5 years of experience received 1 point.

The distances that had to be kept between the workers under conditions of maximum risk (in which all the characteristics receive a score of 5 points) were defined by the focus group based on the footprint of the hazards identified in the JSA for the activities carried out by these workers, such as the typical height of a concrete wall that might overturn, the sufficient braking distance for a forklift, and the distance welding sparks might travel. Based on these distances, on the scores that had been defined for the workers and on the observed site conditions (which included in this case different subcontractors and language barriers between foreign workers), the minimum required distance between each pair of workers was calculated using Eq. (8) (Table 1).

Once the required distances between the workers had been calculated, these could be compared with the actual distances between workers carrying out the activities on the site. To document these distances, the activities carried out during the production of 40 units were observed over 4 days, and the average duration of each activity was measured. The paths along which the workers carrying out the activities were expected to move over time were defined as polylines in a time–space diagram (Fig. 8). By measuring the distances between the polylines in MATLAB, using Eq. (9), instances could be identified in which the distances between workers were expected to be less than the minimum safe distances that had been previously defined. Insufficient distances were identified as likely to occur on two specific locations on site, involving the following workers (Fig. 6):

- A production worker and a worker unloading stone panels
- A worker carrying out finishing works and a worker removing the finished prefabricated walls.

Following this, the planning of the activities could be adjusted by the managers, in order to prevent these unsafe situations. Since the rescheduling of the activities proved to be difficult to implement, changes were introduced instead in the layout of the site. For example, the locations at which finished walls would be stored were changed in order to add space buffers between the workers and avoid the dangerous proximity between the worker carrying out finishing works and the worker removing the finished prefabricated walls.

## 5. Conclusions

A methodology has been developed for analyzing and if necessary adjusting the planned locations of workers on construction sites, in order to prevent the hazards that occur due to an excessive proximity between different workers. Such hazards may occur due to the impact that an activity has on the safety of workers carrying out other activities in adjacent locations on the site. This research focuses on the proximity between workers, since they often display a dynamic and complex behavior that is difficult to model, and since this problem has not been sufficiently studied so far.

The proposed methodology includes a matrix-based method for the definition of safe distances between workers, and the use of 3D time–space diagrams to analyze the existing construction plan. These tools allow the manager to take into account the dynamic activities of workers on sites, as well as the characteristics of individual workers which may reinforce or counteract risk factors. In future research the methodology can be expanded to take into account vertical spatial relationships on the site as well.

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