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GIS-based resource integrated progress tracking for construction projects using spatio-temporal data

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Abstract: In resource-driven and repetitive construction projects, location of resources is a key indicator of the status of the project. A number of methods have been proposed in the literature to integrate resource location information into construction processes. However, there is no method and visual support tool that can depict the movement of construction resources during different time intervals and integrate it with corresponding project schedule. In this paper, a Geographic Information System (GIS)-based 3D (2D location + 1D schedule) framework is developed to visually integrate the construction schedule with the movement of the required resources. The developed framework uses the time geography concept to formalize and visualize both spatial and temporal aspects of the activities' resources on a GIS platform. GIS uses location as the basis of data management for organizing project delivery information. On the other hand, Time-Geography uses space-time volumes to represent the possible locations of a mobile agent over time. As a result, this method presents construction activities' resources and their possible interactions as spatio-temporal prisms. The method focuses mainly on linear construction projects such as highways, bridges and pipelines. The outcome of this space-time GIS platform enables contractors and project managers to track the progress of construction activities at each time interval. As such, this research offers a useful analytical platform to control linear projects, taking into account availability and location of the resources required for executing project activities.

1 Introduction

The poorly controlled and thus uncertain environment of construction projects makes the construction industry to still remain one of the most challenging industries of all (Bosché, et al., 2010). Having accurate and up-to-date information of each construction activity, its respective resources, and their locations can have large impact on effective project control, scheduling and site management. This becomes even more important when coming to linear type of construction projects, where construction resources are often required to repeat the same work in various locations of the project. Due to this frequent resource movement, it is important to continuously integrate location and movement of these projects' resources into the schedules and the control systems.

Control of linear projects has always been a challenging task for construction management (Hassanein & Moselhi, 2005). These projects usually require large amounts of resources which are used in a sequential manner. Due to the size of most linear projects, resource planning and management play a vital role in the successful implementation of these projects. Construction resources used in this class of projects must be properly and efficiently managed in order to guarantee their successful implementation within the planned budget and schedule. None of the traditional linear scheduling methods presented in the, e.g. (O'brien, 1975; Stradal & Cacha, 1982; Harmelink & Rowings, 1998; Harris & Ioannou, 1998) have the ability to be updated based on the availability of resources at each time interval during the project execution.

In order to have more efficient control over actual progress of linear projects, the locational data of the construction resources needs to be continuously visualized and also integrated with the schedules. For this purpose, location aware technologies can be used as an effective means to derive the locational information of resources. Also, Geographic Information System (GIS) technology helps to visualize and store the spatial and temporal data received from the location aware technologies. This paper proposes a framework that integrates locational data of construction resources, received from location aware technologies, with the Linear Scheduling Method (LSM) as the resource-driven scheduling method on a GIS platform. This integrated visualization framework can potentially support decisions pertinent to project control and progress reporting. In the proposed framework, the movement patterns and the location of resources (i.e. crews and equipment) are visually tracked and can be used not only to be aware of the status of each activity, but also as a key indicator of the crew productivity.

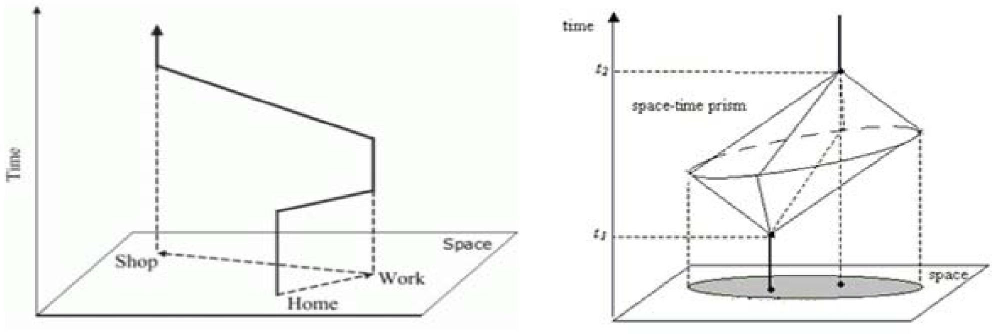
As a result, the framework has the potential to be applied to better control different stages of linear projects. these applications include, but are limited to the following; first, by having the movement patterns for different activities' resources, possible zones of congestion in the construction site, activity idle times, and needs for corrective actions can be identified. Further, by knowing all possible productivity rates for the linear activities, decisions can be more easily made to finish project earlier than planned by using faster productivity rates. In other words, having all possible production rates for linear activities along with the location of resources at different time intervals can highly contribute to an efficient project control system. The essence of using the method is demonstrated by taking preventive action when delays are anticipated to happen instead of "after the fact" remedies when delays already occurred. In addition, the method will also help decrease delays to their minimum possible, and accordingly prevent more cost overruns. Consequently, contractors and project managers of all kinds of linear projects can highly benefit from developments made in this study to track progress of their under construction projects. Through the suggestions made by the developed method, they will also be able to get their projects back on track when the project has not progressed as expected due to resource unavailability or productivity reduction.

2 Background

Construction industry has dynamic environments in which tracking activities and accessing related information are challenging tasks. Failure in performing such tracking in effect way may result in schedule delays (Ergen & Akinci, 2007). Early detection of actual or potential schedule delays is vital to the success of the project in meeting time and cost objectives of a project Identifying spatial-conflicts between activities and their respective resources in construction sites provides the potential to minimize such delays. Since in linear projects, any deviation from planned production rates for activities may result in spatial conflicts between their respective resources, more than one feasible production rates would better be considered. Such spatial conflicts can occur during any period of project execution. Thus, it is important to continuously track and visualize the activities of linear projects to better control their progress. Further, employing Time-Geography concepts help to consider all production rates for the activities' resources.

Bringing locational information into construction processes has started and been widely used during the last few decades. With the recent growth of sensing technologies, real-time and automated project data collection and transmission becomes more available and feasible. The use of these location aware technologies in keeping oversight of resource locations and status of job sites has long been reviewed by different authors (Teizer, et al., 2008; Yang, et al., 2010; Yang, et al., 2011; Teizer & Vela, 2009). The rationale behind all these studies is that tracking workforce and other construction resources provides significant information for productivity analysis, progress evaluations and safety management (Yang, et al., 2011; Gong & Caldas, 2010). . As such, they assessed the suitability of using different location aware technologies to solve individual locating and tracking needs in construction projects (Teizer, et al., 2008). Studies show that location aware technologies can be efficiently used to track construction resources, as well as project status.

Using these location technologies have paved the way to better illustrate individuals' movement trajectories and thus been used in utilizing Hägerstrand's Time-Geography (Hagerstrad, 1970) concepts; i.e. space time paths and prisms (Murakami & David, 1999; Stopher & Wilmot, 2000; Hjelm, 2002). These concepts resulted in better understanding of mapping movements through space and time (Carlstein, et al., 1978). The essence of Time-Geography is the construction of a visually appealing space–time prism to depict and demonstrate the time and space allocation of human activities and movements (Kraak, 2003). The space-time path traces the movement of an individual in space and time (Miller, 2005). The faster the individual travels, the steeper the slope of the path segment will be, since at higher speeds, the same amount of time can be traded-off for more distance, and at lower speeds the inverse is true. The space-time prism is an extension of the space-time path. It gathers all space–time paths an individual might take based on a specific time budget. The space-time prism also measures the spatio-temporal limits of reachability, the maximum velocity of physical movement, and the minimum time required for an activity. Figure 1 shows an illustration of a) space-time path and b) space-time prism.



(a)

(b)

Figure 1: Realization of a) space-time path and b) space-time prism

In particular, Time-Geography-based analysis can be more applicable in scheduling of linear projects where the movement pattern of resources plays an important role in knowing the status of a project. Geo-visualization is a powerful tool for exploratory data analysis of large spatiotemporal datasets. The space–time GIS approach offers an integrated space–time analysis environment that can effectively represent and organize space–time paths and prisms.

The unique ability of =GIS to capture, store and manage spatially referenced data has made this technology to be applied into construction processes (Miles & Ho, 1999). Particularly, its capability to visualize spatial data and to integrate qualitative and quantitative data through spatial relationships enforces its use in controlling construction processes. As a result, GIS is used for different purposes in construction industry including generating subsurface profiles, cost estimating, site and material layout management, real-time schedule monitoring system, route planning, topography visualization, and others. (Bansal, 2007). Bansal and Pal (Bansal & Pal, 2007) propose a method to utilize capabilities of GIS to store spatial data in different themes in order to build cost estimation profiles. Managing site layout and reducing possibility of space conflicts among activities and resources is also one of the benefits that GIS has brought into construction processes; e.g. (Bansal, 2011; Cheng & O'Connor, 1996; Cheng & Yang, 2001).

Cheng and Chen (Cheng & Chen, 2002) also developed an automated schedule monitoring system by using GIS to assist construction managers to control erection process for precast building construction. These studies have all demonstrated the benefits that using GIS technology can bring to construction industry. Detecting construction delays entails prompt identification of delayed process and communication of discrepancies between actual and as-planned performances. Therefore, visualization of construction progress helps construction project managers to study spatial aspects of as-built and as-planned performances, identify progress discrepancies, better utilize resources in different locations and make timely corrective decisions (Golparvar-Fard, et al., 2009).

The method presented in this study tends to add to the body of knowledge of construction management, by integrating all the above mentioned useful tools in one framework. It aims to generate, track and update project schedules for linear projects at certain pre-set time intervals using GIS. For this purpose, an extension to ArcScene is generated within GIS environment that utilizes Time-Geography space-time paths and prisms, to track schedule using locational data acquired from location aware technologies.

3 Proposed method

The method presented here generates a schedule monitoring system that integrates location aware technologies with Time-Geography concepts in a GIS platform. Time-Geography and GIS together can provide a useful analytical environment to visualize and explore activity progress data in a space–time context. For this purpose, a space–time GIS implemented as an ArcGIS extension to facilitate spatiotemporal representation of linear activities. This extension was implemented in ArcScene, which is the 3D viewer of ArcGIS. The method utilizes locational data of the activities' resources as an indicator of activity progress at each time interval.

It should be noted that the method uses the locational data as an input. In other words, the locational data received from location aware technologies presented on GIS raster files inputted into the method as the platform demonstrating actual project location. The Time-Geography concept then can be used to constantly comprehend and detect movement and identify the exact and/or potential location of the resources at each time. Further, the interval times to collect the data is set based on the requirement of the project for how updated the locational data needs to be received. While this is not the case for many projects, but if needed, the project can be instrumented by the right technology to even have a real-time updated data at all time

The proposed method has two phases: 1) generating as-planned linear schedule for the project using time-geography space time prisms; and 2) continuously track progress of activities and the project at pre-set time intervals and update project schedule. Figure 2 illustrates the flowchart of the method. The two phases of the method are explained in the following sections.

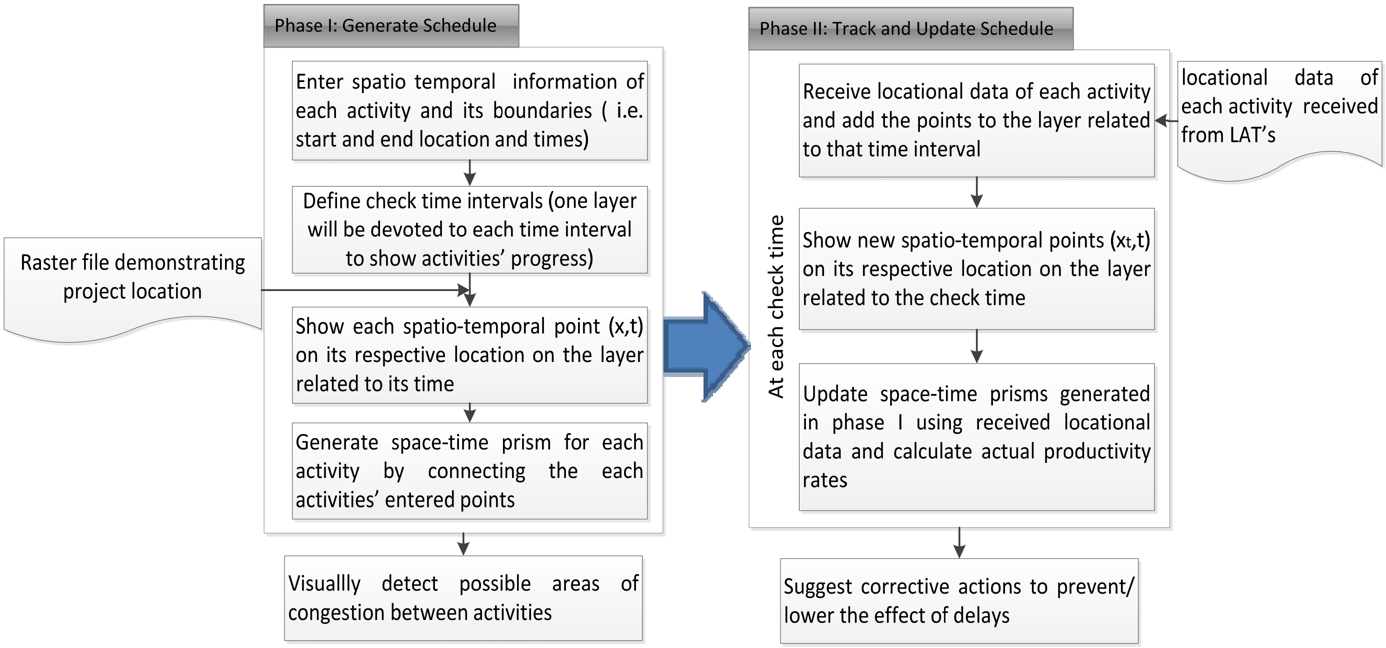


Figure 2: Different phases of the proposed method

3.1 Phase I: Generate as-planned schedule

The Linear Scheduling Method (LSM) is proposed to be used in the control and scheduling module. LSM shows location information of activities as well as both time and distance buffers required between repetitive activities.

To detect the movement patterns of resources, the changes in the locations is comprehended using the Time-Geography concepts. According to the Time-Geography concept, each spatially dispersed activity implies the existence of spatial anchors, i.e. pre-determined locations where an activity must take place. Likewise, in construction of linear projects, each activity is not only associated with a duration, but also with locations showing where it starts and/or finishes. These activities' start and end locations are considered as the anchor points of space time prisms. Therefore, the start location of each activity is considered to be the origin and the movement continues towards a destination point which is equivalent to the location where the activity is deemed to finish.

In the construction industry, labour productivity is the physical progress achieved per hour, e.g., p/hr per linear metre of conduit laid or p-hrs per cubic metre of concrete poured (Dozzi & AbouRizk, 1993). Converting this definition to time-geography concepts, the slope of the space time paths in each time interval can be used as an indicator of crew productivity in that interval. In other words, since the space-time path is the realization of a space-time trajectory, showing actual movement of individuals in space and time, its slope is representative of the space traveled in unit of time. In linear projects, that slope could well represent the productivity in construction. Vertical paths accordingly demonstrate idle times in an activity when no productive work is performed. The optimum path is the line slope equal to the planned productivity.

In order to show each of these points in a spatio-temporal environment, an extension is generated in ArcScene. The extension is coded in VBA environment integrated with ArcScene. To generate the space time prisms for each activity, first project location and environment needs to be identified. For this purpose, first the raster file including the spatial information of the project location is to be inputted (see Figure 3-a). This file can be an image, or a map file. Geo-referencing involves assigning real-world coordinates to a number of reference points on the image. The image is then geo-referenced using control points. These control points in the purpose of this paper are considered to be the start and end points of the project.

Subsequently, to draw the space-time polygons for each activity, an input feature class must be added to the ArcScene. The input feature class must have an appropriately defined projected coordinate system. This input dataset includes ID for each activity (or the resource carrying out that activity) in addition to the coordinates and two time fields (starting and ending time fields) for those activities. The z axis on ArcScene is considered as time axis for this purpose. As such, different layers are defined for start and end times of each activity. Respective anchor points for each activity are placed on these layers and then are connected together, showing the planned productivity rate for that activity. A possible space-time path in this concept is defined as any realization of the resource movements projected from the start point to the end of the activity. However, such path should not have a slope less than its respective acceptable productivity rate as will be described subsequently. Figure 3-b shows the layers created for start and end times of different activities.

In order to draw respective space-time prisms for all possible productivity rates of each activity, prism boundaries and anchor points are needed. These boundaries represent the maximum and minimum possible productivity rates for resources in which all other possible paths can lie in between. The minimum productivity rate can be zero, meaning that the activity can be stopped for some time. This, as known, is the definition of activity floats in construction scheduling. Subsequently, based on the maximum and minimum acceptable productivity rates for activities, the respective space-time prism is drawn. Such space-time prism show all possible paths between stated anchor points (start and end points of the activity) for each activity. Subsequently, in order to generate prism boundaries, separated layers are defined for the points of intersection of maximum and minimum productivity rates.

By drawing space-time prisms for all activities within a project network, possible areas of space overlap or crew congestion can be detected (see Figure 4-a). In these situations, the space-time prisms of those possibly interrupted activities shows overlaps. The intersection areas show when and where (in time and space) such an interruption/congestion is more likely to happen. The possible congestion areas, where the largest overlap happens between space-time prisms of moving resources required for different activities, show places where immediate actions should be taken in order to avoid productivity decreases. Subsequently, management decisions can be taken to minimize such congestions. As a result, the forecasted finish times of activities might need to be revised which accordingly influences all successors of that activity. These data are then transferred to the control and scheduling module to update the schedule and plan for corrective actions, as needed.

3.2 Phase II: Control and track the progress

After the project schedule has been generated in the first phase, check time intervals are defined for the project. At these check times, locational data of resources executing under construction activities are collected and recorded in a database. By assuring receiving of the most updated data, the method would be able to more precisely track the status of the resource movements and project in general. This database is then transferred to the developed application. A layer is then defined for the check time interval. Based on the collected data of the resources during sensing process, the actual paths are identified. The locational data received from the database is shown on the check time's layer. The actual paths are generated by connecting these new points to the points detected in previous intervals. As it can be seen in Figure 4-b all possible paths are updated based on the tracked movements of resources at different time intervals and will be compared with the optimum paths. The dashed line in this figure shows the optimum previously planned path for the activity.

It can be concluded form that figure that because the observed productivity is less than the planned productivity, the productivity in the following time intervals should be increased in order to finish the activity within its time budget. The updated schedule is then compared with the basic schedule to determine the current status of the project. Based on the tracked movements of resources and comparing gained productivity rate with planned productivities, different corrective strategies can be applied. These strategies include but are not limited to the following:

Observed productivities can be used as a measure to calculate finish time of activities. Therefore, possible late or delayed activities can be detected and corrective actions can be taken. Also, in the case where the actual space-time paths show idle time, scheduled start and finish times of the activity itself and the whole project should be revised. In such a case, in order to better manage the project's crew continuity and resource control, the idle resources can be assigned to activities scheduled to perform in neighbouring locations.

A simple example has been used to show the visualization capabilities of the generated model. The project is to renew the surface of an arterial road near McMaster University, Canada and contains 4 activities. The project is assumed to finish on 16 days. The check time interval is considered to be 4 days. Figure 3-a shows the map of the construction site while Figure 3-b shows the different time layers corresponding to end time of each activity. As it is illustrated in that figure, the end layers are chosen of less transparency to make the visualization more clear. Figures 4-a and b demonstrates realization of how space time prisms are generated and updated through different phases of the proposed method. As it can be seen in that figure, when considering only optimum productivity rates for activities, no chance of interruption among activities exists. However, when considering all possible paths for the activities, i.e. by drawing space time polygons, possible time and place of congestion in construction site can be visualized.

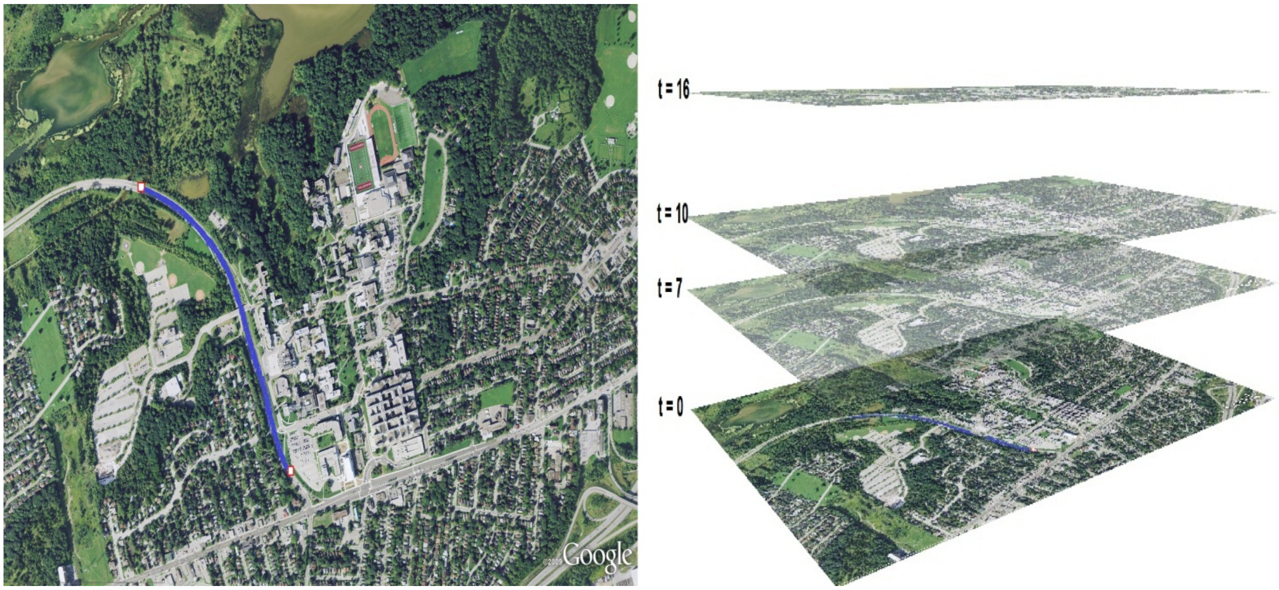


Figure 3: a) construction site's map b) different time layers set for end times of activities

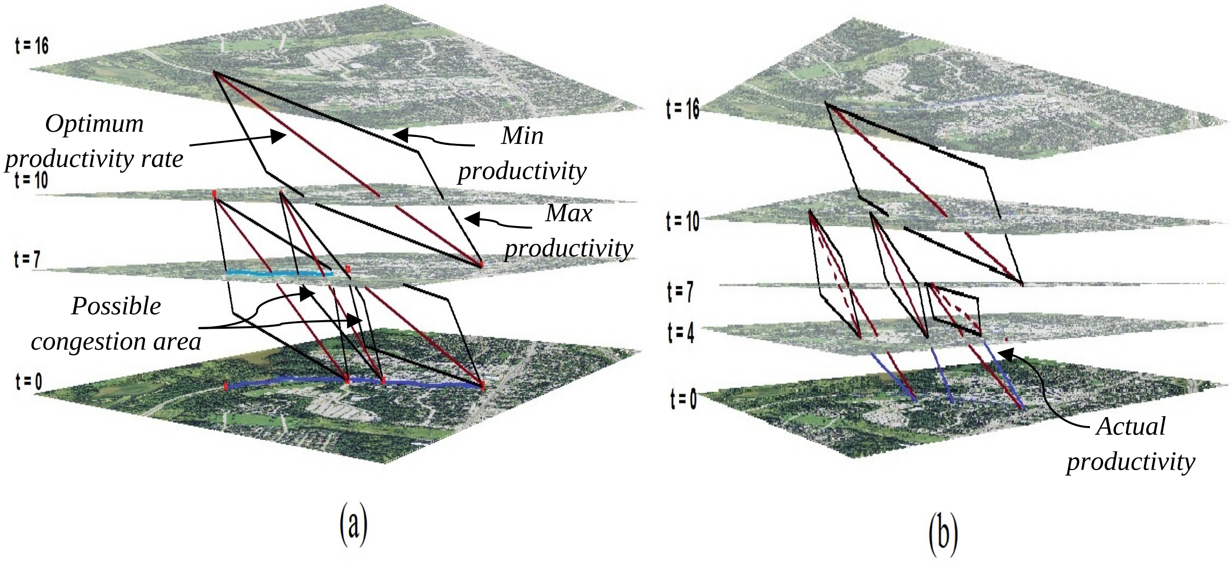


Figure 4: generated schedule in phase I (at t=0) and b) tracked schedule in phase II (at t=6)

4 Summary and Concluding Remarks

This study proposed a new control system for linear repetitive projects using location awareness in construction. This control system aims at addressing the limitation of the current scheduling methods for linear projects by taking exact location and movement of the resources at each time into consideration. It also tends to visually generate and track schedules, by tracking their respective resources, in one environment. As a result, the proposed method integrates location of the resources of linear projects into their linear schedules. To do so, Time-Geography concepts along with location aware technologies were utilized on a GIS platform. As a result, the movement patterns of activities resources (i.e. crews and equipment) have been used not only to be aware of the status of each activity, but also to be used as a key indicator of the crew productivity. This way, by having such patterns for different activities' resources, possible zones of congestion in the construction site, and activity idle times can be identified. In other words, knowing the exact or near exact location of required resources for each activity (or set of activities) and visually integrating such information with a project schedule, leads not only to more practical, updated, and executable schedules, but also to more efficient project control. These locations are considered as indicators of activity status. Consequently, management decisions and corrective actions can be made to prevent/treat the identified issues.

To demonstrate the use of the proposed method and to illustrate its capabilities, a simple numerical example has been analysed. This example shows that by visually generating and tracking project schedule, congestion times and areas can be identified before they occur. By bringing all the necessary elements of a successful control system, i.e. timely schedule, exact location and movement of resources as well as activities actual progress, the method provides an efficient tool to the body of knowledge of project management. In fact, by knowing all possible productivity rates for the linear activities, decisions can be more easily made to finish project earlier than planned by using faster productivity rates. Also, taking preventive action when delays are anticipated to happen is another feature which helps project managers to prevent “after the fact” remedies when delays already occurred. Such control system can also decrease delays to their minimum possible, and accordingly prevent more cost overruns.

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