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Construction spatial modeling and scheduling with three-dimensional singularity functions

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ABSTRACT

Previous approaches for construction project scheduling have been limited to one dimension of time for bar charts and two dimensions for linear and repetitive scheduling approaches, which added a measure of work quantity. The question therefore arises if and how it is possible to derive a three-dimensional and ultimately multi-dimensional model. Reviewing mathematical theory finds that traditional functions lack the capability to express intervals for activities. Singularity functions are therefore chosen to newly derive stationary and directional activities in a Cartesian coordinate system, wherein the two dimensions of the floor plan area plus one dimension of time are explicitly modeled in an integrated manner. They are implemented into a conflict-avoiding heuristic scheduling algorithm that minimizes total project duration, which is computerized and validated with example calculations.

1. Introduction

Space is an important resource type, which is required for and impacts all construction projects in diverse ways. Its special role is related to its three-dimensional nature, with two dimensions of area plus one dimension of height, and the fact that construction activities consume space in two ways, temporarily by occupying and releasing a limited workspace and permanently by installing actual physical facilities. Spatial considerations therefore play an enormously important role in planning and executing the construction operations. From setting up the site layout for creating a temporary factory in the field, via planning and controlling the phases and steps of the growing structural frame of the facility itself, to installing its systems, assemblies, and the exterior and interior finishing elements: Optimizing the space use adds a significant level of complexity to the challenges that construction managers must overcome in their professional practice. This paper therefore presents a new scheduling approach that explicitly considers a workspace component.

1.1. Literature review

Traditional scheduling applies the *critical path method* (CPM) to a network representation of the schedule, explicitly considering sequential dependencies between activity starts and finishes. It is practiced ubiquitously in North America [1]. Methods have been developed to address resource constraints, which primarily add certain algorithmic steps to this existing scheduling technique. For example, Christodoulou [2] required that a CPM analysis had been performed previously to determine total float as an input for his ant colony optimization algorithm, where it served to sort activities by utility. Addressing resource leveling with multiple activity shifts within a multi-objective optimization context, Jun [3] defined new metrics to minimize fluctuations over time, but likewise performed post-processing by shifting resource-loaded activities in a CPM schedule. Aslani [4] noted that CPM yields infeasible results in light of resource constraints and employed dynamic programming to allocate limited resources among competing activities in a manner that sought to prevent extending the critical path. Kim and de la Garza [5] noted that float and critical path are incorrect in for resource-constrained schedules and presented their modified version.

An entire knowledge area, much of it outside construction management research, is dedicated to the *resource-constraint project scheduling problem* (RCPSP). It focuses strongly on optimization algorithms and their efficiency, as surveyed by Herroelen et al. [6], who noted the prevalence of employing CPM assumptions and concepts in analytical approaches. For example, Valls et al. [7] examined how steps akin to forward and backward pass of CPM can be integrated with RCPSP.

Another direction has been explored in geographic science. Hägerstrand's [8, p. 10] keynote was the origin of the often-quoted concept whereby people move on *paths* through a cube, which was formed by "collapsing three-dimensional space into a two-dimensional plain

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[sic]… and use perpendicular direction to represent time." Constraints included physical limitations of persons and limitations on movements or relations. The envelope around potential trajectories from and to a base was described as a vertical *prism*; multiple paths could bundled if they share time and space. This concept continues to inspire research toward a "formal representational theory of the dynamic spatial objects of interest in time geography and activity theory" [9, p. 452]. Miller [10] formalized elements of paths and prisms mathematically, categorized relations between multiple paths, and noted that the Geographical Positioning System (GPS) could be used to record paths with high fidelity in conjunction with Geographic Information Systems (GIS). Such data can be converted in real-time into perspective views of space-time-cubes [11]. Recent research allows a probabilistic nature, i.e. dissolving the crisp shape of the prism [12]. Yet emerging applications of such "*time geography*" often assume a network of paths on a map ([13, p. 1225], emphasis in original) that require known 'anchor' locations. Specific directions may be known, e.g. from the home to a work location. Moreover, they focus mostly on recording and analyzing and thus become increasingly fine-grained, rather than on planning and optimizing at a systems level.

A non-CPM direction was pursued by Roofigari-Esfahan et al. [14], who first viewed said prism from a construction perspective and incorporated it into an example of a two-dimensional (2D) linear schedule. In other words, they surrounded the sloping progress lines of each activity with a trapezoidal envelope of its potential progress between anchors at its start and finish coordinates. A computer implementation to optimize linear highway projects was described via a flowchart, but no further theory of linear scheduling was developed; whereas prisms had three dimensions, their example only had two. Beyond project planning, they noted that controlling a project could be integrated with GIS data [15], as was illustrated with a 'layered' conceptual space-time-cube. Less-closely related studies in the area of construction project management itself have focused on questions of site arrangement or spatially conflicting activities under one of four categories:

- First, the challenge of *positioning temporary facilities within areas* was explored to develop decision support systems, e.g. genetic algorithms to assess a generic location matrix [16] or the actual grid locations [17], using approximate dynamic programming [18], or applying an optimization routine of a commercial programming language to a regular coordinate system [19]. Site layout models generated locations of temporary facilities to be optimized by travel time, logistics costs, and crane safety [20]. Apart from Euclidian and Manhattan distances [19], proximity could also be rated as fuzzy numbers [21]. Most models assume a one-way relation between schedule and space; i.e. dependencies are not modified to resolve spatial conflicts between activities. Resource leveling inspired shifting non-critical activities [22].
- Second, spatial relations of construction activities were formalized into initial *topological taxonomies*. These taxonomies captured space needs of different types of activities to provide data for spatial coordination. Space needs of course should reflect at least the shape, volume, and ability to overlap or stack multiple activities [23]. Riley and Sanvido [24] distinguished areas and paths, decomposed space by the nature of its use, and described typical patterns of use, but did not develop any theoretical model. Different relationships (e.g. 'supported by', 'embedded in', etc.) between physical components were delineated by Echeverry et al. [25]. Heuristics can be used to resolve spatial conflicts that arise in schedules [26]. Such conflicts were categorized by their severity [27], but were still represented with traditional bar charts.
- Third, spatial and topological relations were used in computer aided-design [27] and decision support systems [28] to aid planners in *automatically detecting and avoiding spatial conflicts* between activities. These systems provided interactive visual interfaces to create and adjust their plans for space use based on the detected conflicts until a feasible solution was reached. Winch and North [29] noted a lack of space-oriented research and underlined the importance of congestion by identifying 'critical space' their computerized layout tool. Such congestion can be expressed as the absolute and percent value of time and space interference [30]. Once computerized, lean production principles should be applied to managing space in conjunction with resources to achieve a smooth and non-wasteful production flow [31]. Most recently, Bansal [32] studied how the actual topology can be used to improve realism by linking the database of a geographical information system with a computer tool for space scheduling.
- Fourth, a few decision making tools were described in the literature, which *scheduled based on spatial needs and technological relations* between activities. Computer implementations used heuristics and ad-hoc algorithmic rules to schedule activities chronologically once their spatial needs were satisfied. For example, constraints of work space and labor resources were handled by a system that was developed by Thabet and Beliveau [33], which illustrated its calculations not just with a CPM network schedule, but interestingly also a linear schedule, yet without deriving any theory. Their heuristics employed a quantitative measure of space capacity that compared demand versus availability in different zones of the project [34]. The notion of such space capacity was developed further by Zouein and Tommelein [35], whose approach considered that demand and availability can vary while construction is progressing, which was illustrated with an example of placing concrete for walls within a limited area.

1.2. Research need and objectives

Despite these contributions of previous studies, they represented activities in a high-level manner wherein quantitative detailed interactions appear to have been ignored. Overall, noteworthy work in time geography and an early attempt of adapting it to construction notwithstanding, scheduling still can neither explicitly nor comprehensively incorporate the intricate spatial constraints that characterize manufacturing and installing physical components at a fundamental level. It is thus envisioned that modeling and managing detailed daily interactions between activities will yield more relevant and efficient space plans with shorter durations and more effective use of limited site space. Linear schedules – inherently containing one dimension more than CPM – appear to hold the greatest potential for further development. Their strength lies in planning and tracking progress, because they display curves for each activity in a coordinate system of time and work quantity. The latter often takes the form of distance on horizontal or height on vertical projects. This paper will consequently add to the body of knowledge by introducing a mathematical model for space scheduling that uses singularity functions to represent how the activities progress over time and space, in as much detail as input data will allow. *Research objectives* are thus fourfold:

- To categorize how activities may behave within they three-dimensional (3D) spatial–temporal environment to contrast such modeling requirements with traditional mathematical functions in the 3D coordinate system of a Cartesian space;
- To create new mathematical theory that comprehensively expresses the different types of activities and buffers plus transformations that are needed to enable a scheduling algorithm;
- To derive a scheduling algorithm that must correctly handle spatial–temporal configurations that may be encountered in construction projects, to minimize their total project duration;
- To validate the algorithm with an example by comparing its computer implementation with manually calculated values and draw conclusions on theoretical and practical implications of employing this novel scheduling approach.

The remainder is structured as follows: Section 2 on representing spatial–temporal attributes of activities; Section 3 on formulating singularity functions for different types of activities, their buffers, and