Spatial-temporal reasoning in construction scenes using advanced directional relations*

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Visual spatial-temporal (4D) modeling technologies play an important role in the realization of complex construction projects and programs facing the problems of trustworthy planning, advanced communication among stakeholders, better utilization of critical resources and effective coordination of works. Popular commercial 4D modeling systems provide basic functionality to simulate project activities in space dimensions and across time, but are still limited in validation of project schedules against possible spatial-temporal conflicts, particularly, in identification of such situations as missing supporting neighbouring elements and unsteady element placement. In this paper an approach is proposed to validate construction project schedules based on spatial-temporal reasoning formalisms and methods. We provide a brief overview of currently available qualitative spatial reasoning calculi and argue the need of advanced directional relations. Three sorts of advanced directional relations have been proposed and discussed in conformity to the declared validation problems and developed methods. As expected, their introduction into industry would enable anticipation and avoidance of potential problems at earlier planning phases and would allow reducing risks and waste at final construction phases often undergone delays and reworks.

Keywords: *4D modeling and planning, gravity simulation, spatial relations, spatial-temporal reasoning.*

1. Introduction

4D modelling technologies and tools have tremendous potential to improve design and construction processes due to more careful spatial analysis and improved coordination of planned project activities [1]. They imply advanced spatial temporal reasoning [2] in complex 4D modeling environments. Such environments are formed by means of the consolidation of 3D models prepared using the CAD tools and scheduling information delivered from the project management systems. As a result, individual CAD elements and proper project activities are linked together under predefined dynamic behaviour patterns. Such patterns may include:

— Installing object at specified position in the scene. Typically object appears in the scene when corresponding activity starts;
— Removing specified object from the scene. Usually object disappearance linked to the end of corresponding task;
— Moving object along the specified curve. It is necessary to note, that object position continuously changing, while corresponding activity is in progress, which dramatically increases dynamics of the scene.

Due to the increasing complexity of the recent construction projects and programmes, 4D modelling environments may consist of thousands and millions of individual objects with their own geometric representations and dynamic behaviours. These objects may be both solid bodies given by constructive solid geometry (CSG) or boundary representation (BRep) as well as shapes represented by analytical forms or approximated by polygons collections. All the object motions are assumed to be deterministic being driven by predefined scheduling activities. Another principal feature of the 4D modelling environments is their hierarchical organization induced by work-breakdown structures of the project plans and nested multi-level representations of CAD assemblies. Thereby, the complexity of individual objects and whole environments can be extremely high.

Traditionally, a main attention in the literature is paid to qualitative spatial-temporal reasoning which is based on commonsense abstractions of quantitative temporal and spatial relations peculiar to physical reality world. As opposed to quantitative reasoning based on exact numeric estimations of object relations performed across space and in time, qualitative constraint calculi allow rather inexpensive computations while preserving ease of human comprehension and expressive power. Basically, that is achieved because these calculi can be formalized as abstract relation algebras, and the reasoning can be carried out as symbolic computations.

Spatial relations are in general classified into three main categories: topological, directional, and metric (e.g. size, distance, etc.). Although numerous relation models have been proposed during the last decades for each category, we have had to define our own set of operators for some of them to fulfil the contradictory requirements of the computational feasibility and usefulness. The other reason for introduction of our own operators is constantly growing demand of 4D planning field: it requires advanced functionality which cannot be achieved by simply combining existing spatial relation operators. An example of such operator and a concept of a technique designed to continuously validate the construction schedule is

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presented in Section 2 of this paper.
Speaking about the advanced 4D planning projects, we are not allowed to leave temporal aspect out of the discussion. The geometry in the project can undergo significant changes with time, and although simple objects retain the same geometry throughout entire modeling period, it is allowed that their positions may change due to individual behaviors. Therefore, the properties of group entities may change over time and are dependant on a focus time parameter, requiring the system providing project validation functionality to make use not only of spatial relations but of temporal relations as well, most common systems of them based on the Allen's interval algebra [3] and its derivatives. On the spatial side, numerous formalisms have been pointed out over the past 30 years, including Frank's general directions and Freksa's relative orientation and double cross calculi, cardinal direction calculi (CDC), oriented point relation algebra (OPRA), Egenhofer and Franzosa's 4- and 9-intersection calculi, various region connection calculi (RCC), occlusion calculi (OCC) are worth mentioning. These formalisms have been utilized by many researchers for their simplicity and the ease of implementation [4,5,6,7]

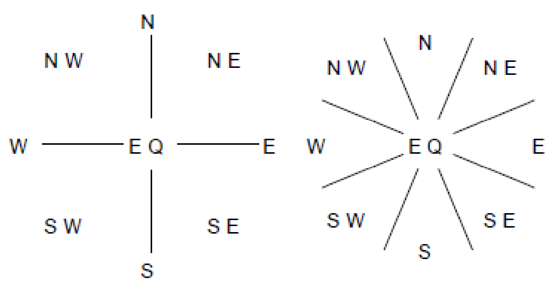

Рис. 1: Frank's cardinal directions

This paper is mainly focused on qualitative directional relations. According to popular definition, direction is a binary relation between an ordered pair of objects A and B in a given reference frame, where A is the reference object and B is the target object. Directional relations were among the first formulated and formalized as early as in 1975 by Freeman [8]. In the last two decades the main reference and starting point which many researchers have been using for their own systems and algebras of directional relations used for spatial reasoning was so-called cardinal directions proposed by Andrew Frank around 1995 [9] This approach might be well-suited for GIS applications, but its main feature – a system of four or eight named directions tied to global Cartesian coordinate system and a set of operators to handle each of them can become a drawback in other applications.

2. Proposed directional relations and operators

Instead of provision and implementation of a full set of such named operators, we propose three basic operators with additional operand D representing the direction in which the relation to be checked (see Table 1). Various sorts of directional relations can be covered by setting particular vector values.

Table 1: Proposed spatial relations and operators

Operator	Relation formalization
InDirectionOf (*A, B, D*)	$\forall b \in B\ \exists a \in A: (\bar{a} \cdot \bar{D}) > (\bar{b} \cdot \bar{D})$
StrictlyInDirectionOf (*A, B, D*)	$\forall a \in A, b \in B: (\bar{a} \cdot \bar{D}) > (\bar{b} \cdot \bar{D})$
SupportsInDirection (*A, B, D*)	$\partial A \cap \partial^D B \neq \emptyset\ \wedge\ A^0 \cap B^0 = \emptyset$ where $b \in \partial^D B \Leftrightarrow b \in \partial B \wedge \left(\forall \varepsilon > 0\ \exists b^0 \in B^0: \left(\overline{b^0} - \bar{b}\right) \times \bar{D} \wedge \left(0 < \left(\overline{b^0} \cdot \bar{D}\right) - (\bar{b} \cdot \bar{D}) < \varepsilon\right)\right)$

2.1 Directional operators for spatial objects

As known, if the entities are not only points but also the geometries with extended boundaries, identification of their relative locations becomes non-trivial. Figure 2 provides meaningful cases in which intuitive identification of the mutual alignment between entities is impossible and needs an additional formalization. For example, it is not clear whether the object A is located above the object B or not. It is also not transparent whether A is located below or above the entities C, D and F. Following early undertaken attempts [10], we highlight a case when the related entities can be entirely separated by a plane perpendicular to the given direction D and, thereby, one object, say A, could be identified as being strictly located in the direction D of another object B. If a plane separating the objects along the given direction cannot be constructed, but it remains possible to separate some parts of one object from another using such plane, we identify the other case as a relaxed condition.
Table 1 provides formal definitions of the directional relation in both interpretations. It can be shown the strict relation is transitive and the relaxed relation is transitive, irreflexive and asymmetric. Scalar and cross products of two vectors formed by the point $\alpha \in A$ and the direction D are denoted there as $(\bar{\alpha} \cdot \bar{D})$ and $\bar{\alpha} \times \bar{D}$ respectively.

It is easy to illustrate the relation by choosing D to be oriented vertically up. In this case it can be reduced to the following trivial forms:

$$Above(A,B) \Leftrightarrow \forall b \in B\ \exists a \in A: a_z > b_z$$
$$StrictlyAbove(A,B) \Leftrightarrow \forall a \in A, b \in B: a_z > b_z$$

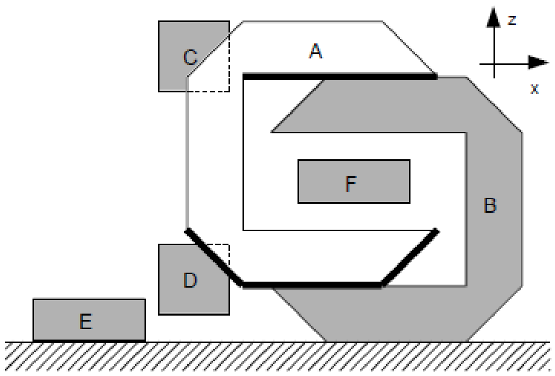

Рис. 2: An example of an uncertainty in the vertical spatial arrangement of a set of objects

Following the example pictured in Figure 2, we can deduce object A is located above B, D, E, and F in the relaxed sense and above object E in the strict sense.

2.2 Support operator

Another operator of the considered group is intended to qualify whether the object A does support the object B in a given direction D rather than simply occupies position in this direction. It can be formalized by defining supporting boundary $\delta^D B$ of object B as a subset of its boundary with neighboring interior points located along the given direction D. In Figure 2 the supporting boundary of the object B is highlighted with bold lines on the suggestion that the direction points upwards. In this case the relation helps to determine whether the object B can be placed on top of the object A without any gaps. Let $\underline{\delta}B$ be a supporting bottom boundary of the object B so that

$$b \in \underline{\partial}B \Leftrightarrow b \in \partial B \wedge$$
$$\left(\forall \varepsilon > 0\ \exists b^0 \in B^0 : (b_x^0 = b_x) \wedge (b_y^0 = b_y) \wedge (0 < b_z^0 - b_z < \varepsilon)\right)$$

Then the relation can be formally defined as follows:

$$Supports(A, B) \Leftrightarrow \partial A \cap \underline{\partial}B \neq \emptyset \ \wedge\ A^0 \cap B^0 = \emptyset$$

In the general case the definition of supporting boundary is slightly more complex:

$$b \in \partial^D B \Leftrightarrow b \in \partial B \wedge \left(\begin{array}{c} \forall \varepsilon > 0\ \exists b^0 \in B^0 : \left(\overline{b^0} - \overline{b}\right) \times \overline{D} \wedge \\ \left(0 < \left(\overline{b^0} \cdot \overline{D}\right) - \left(\overline{b} \cdot \overline{D}\right) < \varepsilon\right) \end{array} \right)$$

Obviously, this contiguity relation is not equivalent to any directional relation considered above since it employs topological properties of the objects. Moreover, it cannot be expressed in terms of the spatial algebras known to authors today.

Returning to our example, objects B and D support object A since they have intersections with a supporting bottom boundary depicted by a thick line. But, as you can see, only object B has legitimate support below it, and the object D is literally floating in the air. It is crucial to handle such situations during the project schedule where, for example, the construction elements or equipment units cannot be removed before the objects they support or cannot be installed after these objects. This implies checking for contact between the new objects that appeared in the scene and the existing objects located in the same or nearby positions. If an object is removed from the scene, then the remained objects become subjects of gravity checks as they could be resting on the removed object. To perform gravity tests, they must be preliminary specified in a form allowing mathematically strong validation, and this topic is further discussed in Section 2.4.

2.3 Stability operator

More physically sound definition of this gravity-based relation would require computational analysis of the object static stability. It can be performed by calculating the center of mass of the object and its projection onto supporting polygon in addition to its supporting boundary in the given direction. The position of the center of mass might be a predefined parameter of an object or it can be found using well-known algorithms and provided information about density distribution. The following operator demonstrates a particular case of such relation with the gravity vector pointing downwards:

$$SupportsCoM(A, B) \Leftrightarrow$$
$$Supports(A, B) \wedge (\exists a' \in ConvexHull(A \cap \underline{\partial}B) : (a'_x = c_x) \wedge (a'_y = c_y))$$

The definition of SupportsCoM(A,B) requires from the supported object B not only be supported by A as in Supports(A,B) definition, but to have its center of mass c placed in a specific spatial relation: if both the center of mass of B and convex hull of all points in A that support B are projected on a plane orthogonal to a gravity vector (in our case horizontal plane and inverted z-axis respectively), center of mass projection must lie inside the convex hull projection. In physical sense, the latter means that if the center of mass is inside the support polygon, there exist no moment from the gravity force which is a necessary condition for stability [11].

In Figure 3 it is shown that in a), b) and c) object A supports object B: the center of mass (depicted by a bold dot) of the latter is above or below the support polygon (indicated by hatching), and in d) it has the lack of support.

The main advantage of this approach it that it does not require extensive and costly physical simulation and yet can provide adequate results by making use of computational geometry methods only.

2.4 Spatial-temporal reasoning in construction scenes

In order to identify suspicious situations and potential conflicts not only on the small static sets of objects but

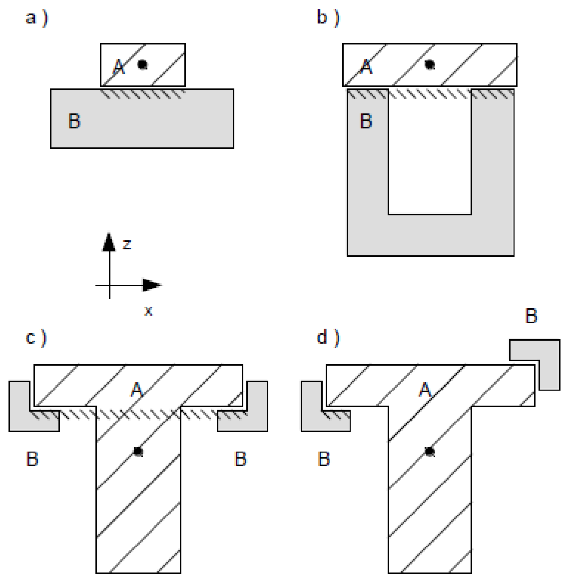

Рис. 3: Supported object, its center of mass and support polygon (vertical projection)

during the entire scheduling period of the 4D project on the whole available dataset it's crucial to specify the method of performing project-scale gravity tests. Let's discuss how such a specification can be compiled being based on the introduced gravity support relation among objects of a scene S.

General specification of gravity tests should include the set of objects $S* \subseteq S$ considered to be a priori installed correctly. By pointing out such objects, we define initially deployed elements of the scene S, such as ground, stationary infrastructure, etc. The specification may also contain information about particular objects and additional requirements assuming the availability of the neighbours for the installed objects in their final positions.

In most practical cases, qualitative reasoning formalisms and relation networks can be utilized for this purpose. Reasoning problems are usually stated as follows: given possibly indefinite knowledge of the relations between some objects (points, intervals, regions, etc.) how do we compute the strongest possible assertions about the relations between some or all objects. Such problems can be formalized using relation networks. Using the composition table induced by corresponding algebra and the path consistency algorithm, these networks can be refined to conclude about new relations between objects and to derive new knowledge about requested objects. Determining exact solutions to this problem has been shown to be intractable. Therefore, approximation algorithms are usually developed based on relation propagation. Sometimes, tractable subclasses of the problem are handled as particular cases to avoid extremely high complexity of computations.

As suggested, an object $o' \in S$ is installed correctly and satisfies to corresponding gravity test if some object $o'' \in S$ has been already installed correctly and the operator $Supports(o'', o') returns TRUE$. In some cases, the direction D (which is upward in general case) should be additionally prescribed to particular objects representing different type of attachments.

The usage of relation networks for gravity conflict identification looks promising enough because of the following features:

- Locality – only spatial neighbours of an object can take part in a binary relation with it – no need to check every object of the scene.
- Incrementality – relation network can be built and maintained incrementally, allowing traversing from the affected objet to its neighbours and checking if they are affected too.
- Homogenity – built around single binary relation, and the corresponding operator will return true or false for a pair of objects without any third option.

It's worth mentioning that our goal in project validation does not lie in the field of exact physical correctness: to achieve this one should employ a physics engine, greatly reducing performance which is very costly on computational and human resources – if possible at all – for the projects of such complexity and scale. Instead, our goal is to make use of rather simple computational geometry algorithms and already known 3D geometry of the objects to reveal and indicate potentially dangerous situations in 4D planning environments so the user can decide how to deal with them.

3. Conclusion

We assume proposed directional relations and their mathematical formalizations as constructive since they can be validated by means of computational geometry, including collision detection methods in particular. These relations allow effective implementation and usage in 4D planning and modelling systems to provide identification of possible trivial and non-trivial conflicts originated from the construction project scheduling problems. A software library utilizing various concepts presented in this paper is being developed, and some components of this library have been previously approved and successively employed in a few industrial projects. [12]

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