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Construction-specific spatial information reasoning in Building Information Models

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ABSTRACT

In recent years, there have been significant advances in modeling technology for object-oriented building products. However, the building models are still lacking of providing construction-specific spatial information required for construction planning. Consequently, construction planners visually analyze building product models and derive geometric characteristics such as bounded spaces and exterior perimeter to develop detailed construction plans. Such a process presents fragmented information flows, from building product information to construction planning, that rely on subjective decisions of construction planners. In order to overcome these drawbacks, this research proposes a geometric reasoning system that analyzes geometric information in building designs, derives the construction-specific spatial information, and uses the information to assist in construction planning. The scope of presented work includes detecting work packages formed by faces during construction, such as large work faces and bounded spaces, and using information in the work packages directly to support planning of selected indoor construction activities. The main features of the proposed system named Construction Spatial Information Reasoner (CSIR) include a set of relationship acquisition algorithms, building component relationship data structure, and interpretation of the relationship to support detailed construction activity planning. The relationship acquisition algorithms identify adjacency between building components that is stored in the relational data structure. Then, acquired adjacency relationships are transformed into a set of graphs that represent work packages. To implement the proposed approach, CSIR utilized a commercially-available Building Information Modeling (BIM) platform and the algorithms were imbedded to the BIM platform. For validation, CSIR was tested on a real commercial building. For interior ceiling grid installation activities, CSIR successfully detected existing work packages and analyzed the spatial characteristics impacting construction productivity. The major contribution of the presented research would be to enable a realistic analysis of building geometric condition that is not possible in current BIM and a seamless information flow from building product information to construction process plans. These can potentially reduce current manual and error-prone construction planning processes. Limitations and future research suggestions are also presented.

1. Introduction

1.1. BIM and construction planning

Developing an effective construction plan is challenging but critical to successful delivery of a construction project [1,2]. Construction plans often involve many activities, from analyzing various construction site conditions, preparing construction equipment, tools, and temporary facilities, to assessing the feasibility of developed plans. Traditionally, such construction planning activities were conducted using two- or three-dimensional building drawings along with construction schedules in bar charts. Construction planners have to mentally simulate expected construction site conditions and rely on their intuitive understanding about the construction methods [3]. This is because the static views of the buildings cannot visualize dynamic and time-based construction processes, and the construction schedules in bar charts cannot explain geometric conditions of construction projects. Such challenges make construction planning mentally demanding while most construction projects are often short of human resource for construction planning [4].

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Developments in the modeling technology of object-oriented building products, such as Building Information Modeling (BIM), can reduce the intensity of such mental activities. The advanced 3D modeling of BIM enables accurate and consistent visualization of building appearances. Furthermore, Building Information Models (BIMs) can be integrated into construction schedules by establishing virtual links between individual components, e.g. walls and slabs, and schedule activities. Through the links, expected progress of construction plans can be graphically visualized in a pre-defined time interval [5–8]. Since a temporal dimension is added to a 3D BIM, the technology is called 4D BIM. As stated in several research studies, there are potential benefits of using 4D BIM techniques for construction planning. 4D BIM can assist in construction planning process [9], enable an accurate constructability analysis of the construction schedule [10,11], and facilitate collaborations between multiple project participants [12,13].

1.2. Lack of construction-specific information in current BIM-based construction planning

While the aforementioned benefits make 4D BIM one of the most dominant methods that incorporate construction process information into building product information, currently available BIM packages utilize rich information in BIM mainly for visualization of building products and construction processes. Several technical deficiencies have to be overcome to take full advantage of BIM which could assist construction planners in a way that reduces the mental activities required for planning.

First of all, there is a lack of technical capability to derive information relevant to construction from BIM. When a construction plan is established, there are several important issues to be addressed, such as geometric conditions impacting construction progress [14], characteristics of construction method applied [15,16], required temporary structures [17], potential construction hazards [18], spatial conflicts between work crews [19] and availability of work crews, etc. For a construction plan to be practical and executable, construction planners have to analyze a BIM and a construction schedule considering all such issues when they create 4D BIM. Construction planners of today still visually analyze building designs and construction schedules relying on their knowledge and experience since most of such construction-specific information usually does not exist explicitly in BIM [20]. Accordingly, the reliance on mental activities, driven by human cognitive capability, still exists even when BIM technology is used for construction planning.

1.3. Representational deficiencies in current BIM-based construction planning

Another drawback is representational deficiencies in current BIM-based construction planning tools. Today, 4D BIM is created based on virtual links between building components and construction activities. And, the resultant construction process is visualized by making solid models of the components appearing and disappearing according to the schedule. While this can enhance the intuition of project participants about the proposed construction process, this approach cannot analyze the relationships between contextually related components, which is vital for deriving construction-specific information from BIM. For example, when a wall is constructed, the geometric relationship between the wall and a slab adjacent to it has to be analyzed to determine if a temporary system (e.g., concrete form, shores, scaffolding) is required. Also, there are several construction activities that appearances and disappearances of solids cannot represent properly. For example, wall's faces, instead of its volume, better represent wall painting activity. Also, if a concrete slab is constructed by multiple sequential concrete pouring, only a segment of the slab better represents the result of one concrete pouring [21,22]. Furthermore, specific geometric conditions can be formed by a collection of objects. A bounded space (e.g., zone), for example, can be formed by several wall faces and segments of a slab and a ceiling. Thus, in order to derive contextual information from a building design, geometric relationships between geometric entities (faces, edges, and vertices) should also be analyzed by BIM software.

1.4. The need for a context-aware construction planning tools

As such, current practices of creating 4D BIMs are driven by intuitive understanding and knowledge of construction planners, and currently available BIM packages have several representational deficiencies to express realistic construction processes. Thus, labor-intensive mental activities are required to establish construction plans. This drawback prohibits a seamless information flow from building design to construction planning and further downstream construction planning activities, such as crew path planning, temporary structure, and safety planning.

In order to overcome these drawbacks, this research presents a geometric reasoning system named Construction Spatial Information Reasoner (CSIR) that automatically derives construction-specific spatial information from BIM and construction schedule. Since spatial conditions are formed by both geometric shapes of building components and spatial relationships between them [23–25], CSIR analyzes construction site conditions based on qualitative spatial relationships between building components. For that, a set of algorithms were proposed that analyze adjacency between faces of building components, and a new building component data structure was proposed that stores the relational information. In the presented work, the scope of geometric reasoning was limited to detecting work packages formed by building components' faces, such as continuous work faces and bounded spaces. Then, the results of geometric reasoning were used directly to support planning of selected interior construction activities.

This paper is organized as follows. Background section provides a review of previous works in analyzing relationships between building components and previous reasoning approaches in support of construction planning. The algorithm section presents descriptions about the proposed relationship data structure and geometric reasoning algorithms. Then, case study section presents the CSIR software prototype developed on top of a commercially available BIM platform and its implementation for a realistic building model. The last section discusses current limitations of the presented research, expected contributions, and potential future research topics that go beyond the current research scope.

2. Related works

Focusing on construction, this section presents relevant research studies in analyzing product information to assist product analyses and production planning.

2.1. Product-process integration

In several industries, such as manufacturing and the Architecture, Engineering, and Construction (AEC) industry, there have been approaches that use the product models to facilitate automation of product manufacturing and testing. In manufacturing industry, there have been efforts to integrate product Computer-Aided Design (CAD) systems to Computer-Aided Manufacturing (CAM) systems via automated Computer-Aided Process Planning (CAPP) systems [26]. The goal of such transformation, from design to production, is to interpret geometry information of a mechanical component and derive its production plans without human-intervention [27,28]. Specifically, the range of automations includes selecting proper machining tools, generating tool paths, etc. [29].

During design-to-production transformation, features play an important role. A feature is defined as a region of an object that is meaningful for a specific activity or application [27]. Each manufacturing feature describes product parts to be processed by a specific operation, such as drilling and milling. Different features have to be used to describe product parts manufactured by different manufacturing operations. While the features can be used early in product design stages, doing so is not desirable because it can diminish designer's rule and ability [27,28]. Instead, manufacturing features can be detected using a set of pre-defined features after a product design is completed [30]. Various feature recognition techniques were developed to detect features from product designs since most of features are not explicitly expressed in original designs. Among many automated feature recognition techniques, boundary-based recognition is a common approach that detects features from Boundary Representation (B-rep) of a solid [20]. Graph-based recognition, as an example of boundary-based recognition techniques, transforms a component into a face adjacency graph where its nodes and arcs represent faces and edges, respectively. Graph-based recognition approaches base their algorithms on faces and use adjacency relationships between them. Since various geometric conditions in a building design are formed by a collection of faces, these approaches can potentially be used to analyze geometric conditions in a building design. For example, a room can be represented by a set of faces (from walls and slabs) that are adjacent to each other and form a bounded space [31]. However, there is a challenge that prevents applying boundary-based feature recognition techniques to building product models. Since a product model with a continuous and closed boundary condition is required to generate a face adjacency graph, building models composed of a collection of numerous solid objects cannot be converted into a face adjacency graph. A preliminary step is needed that generates the topological adjacency information between building components. Understanding such needs, Section 2.2 provides a review of relevant research studies in analyzing spatial relationships between building components.

2.2. Geometric relationships between building components

Spatial relationships between building components, as well as their shapes, contribute to creation of specific spatial conditions [23]. Thus, it is crucial to analyze the inter-component relationship considering the context of tasks. According to [32], there are three ways of assessing relationships between building components. The first method is capturing relationships when each building component is created in a main building model. This requires many computer memories and reduces the speed of the modeling program [32]. On the other hand, spatial relationships can also be manually assessed by users. A room detection algorithm presented in [31] relies on 'connected-to' relationship between wall faces that is assigned manually. While the room detection algorithm is in simple 2D, expanding the algorithm into 3D space and incorporating the relationships between other related components, such as slabs and ceilings, will enable more comprehensive spatial interpretation in support of construction planning. The constructability expert system for concrete construction developed by the Center for Integrated Facility Engineering (CIFE) in Stanford University requires a user to specify connections between the structural elements each time they are created [15]. Also, the temporary structure type selection system developed by CIFE also requires a user to specify the work face and the base surface manually to evaluate the geometric conditions [17]. Since human cognitive capabilities are used, these manual approaches provide better flexibility and do not rely on pre-defined rules of assigning the relationships. Despite the benefits, manual approaches require a user to have a comprehensive understanding about various different purposes of assigning the relationships [32]. Also, assigning relationships between all building components for all purposes may require an extra-ordinary amount of mental activities due to complexity of construction projects.

The third method uses geometric reasoning or knowledge-based reasoning to derive geometric relationships between objects. Due to the wide variety of the spatial relationships, this requires domain-specific knowledge to be contained in building components [32]. Goto et al. [33] assessed connectivity between beams and columns to transform 2D building design into 3D. Chinowsky and Reinschmidt [34] developed a geometric reasoning system that interprets inter-component relationships based on the project-specific lexicon. The lexicon provides the qualitative project-specific definitions such as 'close-to.' Nguyen et al. [35] presented an algorithm that determines topological relationships between solid components by analyzing outward normal vectors of boundary faces. Also, Borrmann et al. [23–25] developed a set of spatial query languages that derive topological, directional, and metric relationships between building components based on space partitioning algorithms, such as Octree representation and slot-tree.

While the reviewed research studies provide an important theoretical background to analyze relationships between building components, few of those efforts presented a way to convert the relationships into task-specific information. Section 2.3 presents research studies in interpreting building designs based on the characteristics of tasks. While most of the tasks in the reviewed studies were related to construction planning, some focused on the building design interpretations from different viewpoints of design domains.

2.3. Task-specific interpretations of a building design

Depending on the characteristics of design, engineering, or construction tasks, the same building design can be interpreted in several different ways. Riley and Sanvido [36] presented a construction-space model that comprises a set of space demand patterns. Each pattern describes how a typical building construction activity interprets and uses spaces over time. For example, masonry crews can either choose to complete one exterior face at a time or follow a spiral pattern to finish the work. Other activities, such as duct risers and plumbing risers, require work crews to follow vertical or horizontal paths. Similarly, Perspective Approach of [37] pointed a need to construct different views of a design depending on the characteristics of engineering tasks and proposed a formal mechanism of constructing a task-specific view out of other views. While these two studies provide theoretical frameworks to enable contextual interpretation of building designs, they did not present a method to automate the interpretation. Instead, their models can be implemented relying on manual and visual analysis about a building design. Considering limited human resources available for construction planning in most construction projects [4], these approaches can provide a limited benefit for construction planning unless they are automated.

Also, there have been research studies to assist in construction planning by automatically deriving detailed construction schedules from a given building design or by modifying building designs to meet the needs of a given construction schedule. Woodbury et al. [38] stressed the need for reasoning approaches to enable construction automation and developed a prototype erection sequence planner for structural system installation. Their sequence planner transformed dependencies between building components into a CPM-like graph and, by interpreting the graph, a linear order of the construction step was obtained. While this could derive an erection sequence of building components, its capability was limited to pre-fabricated element erections in 2D building structural models. Hu [39] developed an advanced system for the similar purpose. It automatically derived a construction sequence of a structural system based on a connection graph and disassembly order process. Weldu and Knapp [40] proposed a system that automatically generates construction schedules for 4D visualization considering connectivity between components, load transfer between structural elements, etc. While all those approaches attempted to infer construction-specific implications from building designs and construction knowledge, they focused only on pre-fabricated structural components and did not present a method to analyze geometric conditions formed by common building components like walls and slabs. On the other hand, [22] proposed an approach that automatically segments a building component (e.g., a slab) into several construction zones based on a given construction activity (e.g., concrete pouring).

To serve more specific needs, such as constructability analysis and construction safety planning, building designs can also be interpreted using specialized queries. Fischer [15] presented a constructability expert system that incorporates formal constructability knowledge base, computer-readable building model, and the reasoning mechanisms. This system analyzes geometric and topological information of a structural system of a concrete building to provide the constructability feedback during the design stage. While BIM technology of today was not available when the expert system was developed, this research proposed spatial reasoning logics that derive information specific to reinforced concrete building construction from attributes of building components and the relative placements of the components. Fischer and Tatum [16] proposed another expert system that selects proper cast-in-place (CIP) concrete construction methods based on a formal constructability knowledge and computer-readable building design information. Nepal et al. [20] proposed a set of specialized queries to support construction planning. The queries included component intersection and penetration queries, locations queries, spacing queries, alignment queries, design uniformity queries, etc. For example, vertically or horizontally unaligned columns were identified using alignment queries and the result was informed to the formwork subcontractors and construction managers. However, most of their queries function in 2D and under an assumption that building components (walls and columns) are aligned parallel with the *x*- or *y*-axis. Considering the alignments of building components that may vary depending on the design intents, their queries were developed based on over-simplified assumptions. Also, it presented a limited capability in deriving spatial information useful for construction activities. Similar to [20], there exist approaches that automatically analyze building models to support construction-specific automations related to construction safety and temporary structure planning. Zhang et al. [18] presented a rule-based construction safety checking system focusing on fall protection. The safety planning system detects the fall-related hazards from BIM models and proposes solutions to prevent the hazards. Kim and Teizer [41] presented a temporary structure planning system focusing on scaffolding. Geometric reasoning algorithm in the temporary structure planning system detected locations where scaffoldings are required by automatically analyzing spatial relationships between faces of building components. But, it does not have a capability to analyze various conditions presented in [36].

2.4. Point of departure

As reviewed, there have been attempts to analyze relationships between building components (Section 2.2) and attempts to analyze building's geometric conditions to support construction planning (Section 2.3). However, there have been few studies that tried to automatically derive construction-specific information from geometric relationships between building components that are crucial for forming conditions meaningful for construction activities. Due to this deficiency, many practical constructability issues need to be identified and addressed by manual analyzing of 3D building models and construction schedules. For example, locations requiring scaffolds need to be identified by individual engineers manually. Complex room shapes decreasing the productivity of a ceiling grid installation can only be identified manually. Furthermore, while there are many geometric conditions are formed by spatial relationships between several component faces (as discussed in Section 2.2), there are few studies addressing the need to analyze the relationships between component faces to derive information useful for construction planning. Efficiency and accuracy of construction planning can potentially be increased by automatically deriving construction-specific information based on the relationships between building components.

Thus, this research proposes an approach to derive construction-specific information automatically based on geometric relationships between component faces and use the information to assist in higher level construction planning. Specifically, this research presents a systematic approach that detects a set of work packages from a building design and then uses the information to directly support construction planning. As its distinctive feature, a building design is transformed into a set of adjacency graphs to detect geometric conditions that can be considered construction work packages (such as bounded spaces and continuous work faces). Accordingly, nodes and arcs in the graph structure represent faces and adjacency between them respectively. Conventional graph-based feature recognition for manufacturing assumes that a component is in the form of a complete solid where one edge is shared by two faces. Arcs, in those graph structure, are used to represent topological ('connected-to') relationship between two faces.

In order to achieve the goal, this research also attempts to address a challenge in building modeling technology. Unlike many modeling techniques in manufacturing industry, 'connected-to' relationships cannot be derived directly from current BIM platforms because components in a BIM are rarely organized in a way that all the components form a single solid of a building or faces of different components share a common edge. Thus, in the proposed approach, 'adjacent-to' relationships were identified, instead of 'connected-to' relationships, to account for required tolerances. In addition, a new building component data structure was proposed to systematically store the adjacency.

3. Algorithms

This section presents a set of algorithms in CSIR that interpret building designs to support construction planning. Specifically, geometric relationships between components are analyzed, work packages created by several faces (work faces and workspaces) are detected based on their adjacency relationships, and then information in the work packages is used to provide spatial information necessary for construction planning. In order to meet the needs to analyze geometric condition created by faces, the algorithms were designed in a way that face objects and adjacencies between them provide the basis to analyze geometric conditions created by several faces.

Presented algorithms have three main parts: (1) relationship data structure, (2) assessment of adjacency relationship, and (3) adjacency graph generation and interpretation. Brief introduction is presented and detailed explanations follow in the next section.

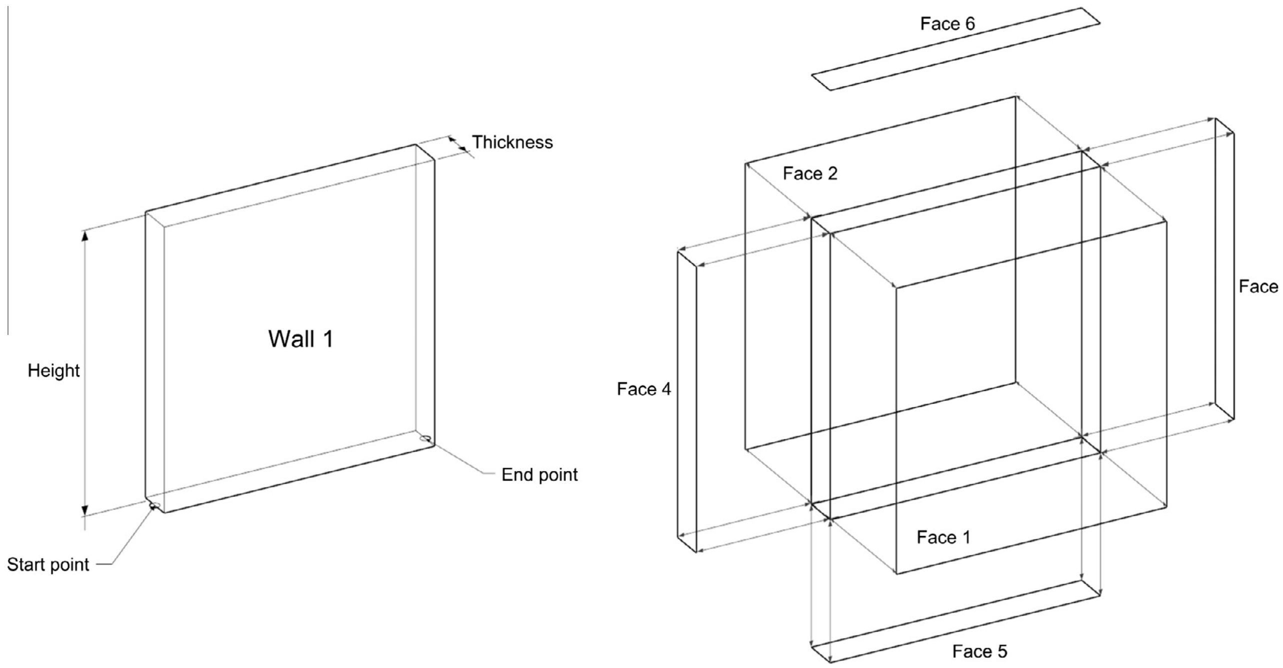

Fig. 1. A wall component (a) and its decomposition into face objects (b).

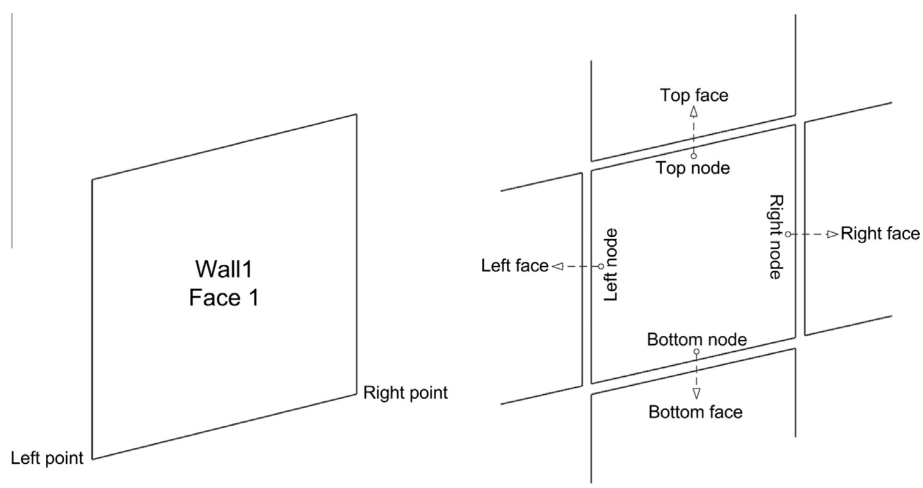

Fig. 2. A face object (left) and nodes (right).

- **Relationship data structure**: is a data structure to enable a face object to store information on its geometric adjacency with other faces. This provides the basis to analyze geometric conditions formed by several faces.
- **Assessment of adjacency relationships**: is an algorithm that analyzes geometric adjacency of a face to other faces, which will be stored in the relationship data structure.
- **Adjacency graph generation and interpretation**: adjacency graph generation is a process of generating a set of graphs where nodes and arcs are face and adjacency relationship, respectively. Graph interpretation is a process of transforming inter-component relationships into construction-specific spatial information.

3.1. Relationship data structure

Geometric relationships between objects (faces in the presented research) are essential in analyzing geometric conditions in a

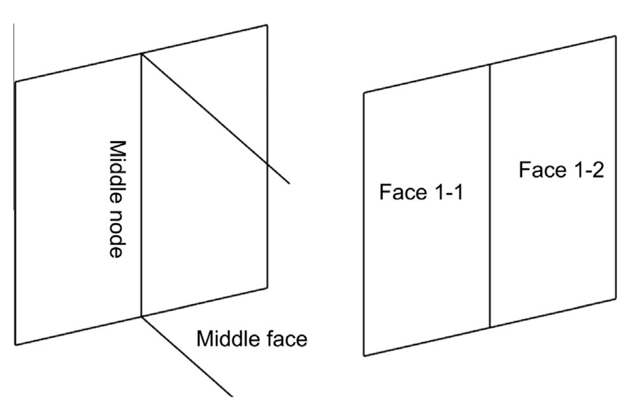

Fig. 3. A face subdivided by a middle node face.

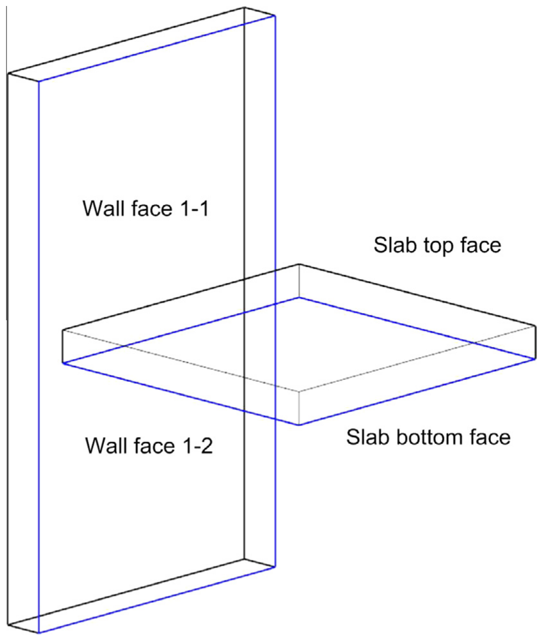

Fig. 4. A slab bottom face as the middle face of a wall face.

building design [23]. However, face objects in BIM tools of today usually contain limited information, such as vertices and surface normal vector. It does not provide sufficient explanations about its spatial relationship with other faces or volumetric components. To overcome this technical deficiency, a data structure was proposed that systemically stores information on how a face of a building component is adjacent to other faces. While the type of relationship is limited to adjacency in this research, several other types of relationships can also be considered as in [23] depending on characteristics of construction activities.

Proposed relationship data structures were established for faces of common structural components, such as walls and slabs. There are various possible types of faces (such as wall face, slab bottom faces and slab top faces) and relationships between them (wall face-to-wall face relation, wall face-to-slab top face relation, etc.). Since one face can be adjacent to multiple faces, its relationship data can have several types of nodes that store pointers to adjacent faces. A wall face is presented as an example to explain specifics of the proposed relationship data structure.

Fig. 1 shows a wall component created in commercially available BIM software, Tekla Structures. Information in a wall component includes start point, wall end point, wall height, thickness, material, etc. The wall's start point and end point are specified by a user when a wall component is created. The geometry of the wall component in the figure is composed of six faces. Each face in a wall component has vertices, edges, and a surface normal vector. Users can obtain all the information either through its user interface or Application Programming Interface (API). In order to incorporate relational information, each wall component was decomposed into its faces and then two largest faces were selected (*Face* 1 and *Face* 2 in Fig. 1b). This approach was applied in [41] that also selected two faces that require a scaffolding in front of them. For selection, surface normal vectors and face areas were used. The selected wall faces should have the largest surface areas and the face normal vector should be orthogonal to the vector from a wall start point to a wall end point.

Then, for each face selected, several types of nodes were generated to record its adjacency with other faces. Fig. 2a illustrates face 1 in Fig. 1. Left point and right point were obtained by offsetting the start and end points of a wall, respectively, by half of the wall thickness. To represent its relationship with other wall faces, five types of nodes (left, right, top, bottom, and middle) were created as illustrated in Fig. 2b. Faces in top, bottom, left and right nodes can form a larger face that a construction activity can progress continuously. On the other hand, a face in the middle node can subdivide the wall face into two pieces as in Fig. 3. Face 1 is divided into Face 1–1 and Face 1–2 by the Middle Face. This represents a construction activities cannot progress from Face 1–1 to Face 1–2 because of a face in front of it.

Similarly, each slab component was decomposed into faces and the faces with the greatest and smallest values of surface normal z-coordinate were selected as top and bottom faces, respectively.

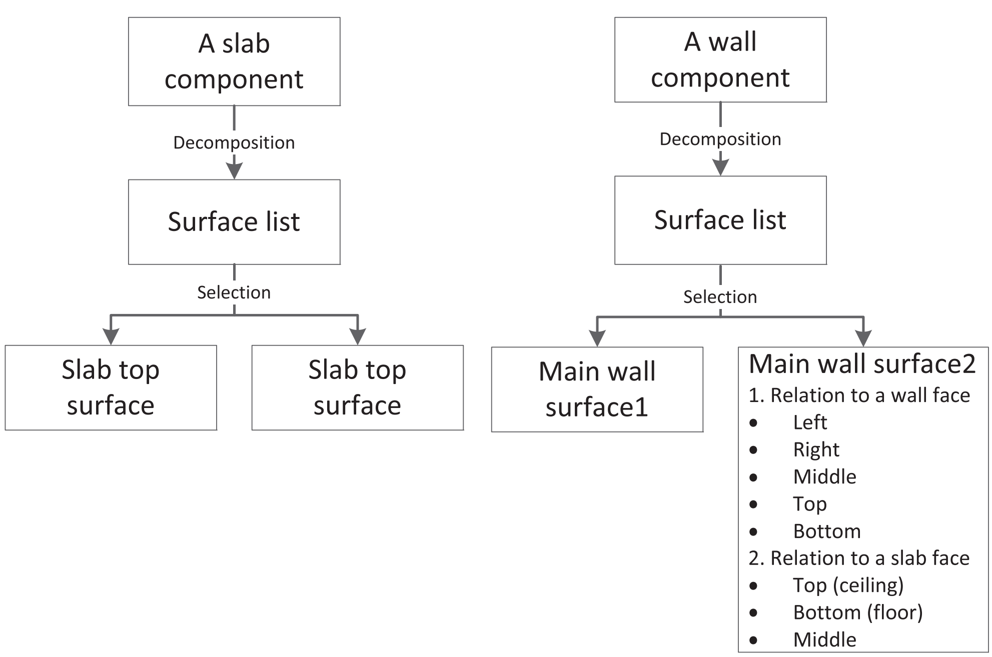

Fig. 5. Hierarchical data structure based on nodes relationship.

To represent relationship of a slab face with wall faces, top, bottom, and middle nodes are created. If a wall face has slab faces in its top and bottom nodes, the vertical movement of a construction worker in front of the wall face is constrained by the slab faces. If a wall face has a slab face in its middle node, the wall face is divided by the slab face. Fig. 4 illustrates a slab in front of a wall. Realistically, the slab bottom face is perceived as dividing wall face 1 into two faces (wall face 1–1 and wall face 1–2) if the two faces are geometrically close. A construction worker cannot proceed to wall face 1–1 after completing wall face 1–2 because of the slab bottom face.

As illustrated in Fig. 5, the node information is managed separately for different types of relationships (wall face-to-wall face and wall face-to-slab face). While the top node for wall face-to-wall face relationship stores the wall faces, the top node for wall face-to-slab face stores only slab faces. As a result of this process, each face in the building components contains nodes that can store pointers to the adjacent component faces.

3.2. Acquiring the geometric relationship between component surfaces

In this step, adjacencies between the faces are examined and nodes in the relationship data are filled with pointers to adjacent faces. Based on the observations of several realistic building models, it was identified that geometric conditions, such as enclosed spaces and continuous faces, are formed not only by connected objects but also adjacent objects. For example, if the distance between two parallel wall faces is one foot, a construction worker can continue painting along the two faces without stopping even though they are not connected in the digital model. Thus, by examining the adjacency instead of connectivity, geometric conditions can be analyzed realistically by a computer using a customizable tolerance.

To assess adjacency, a set of cubic cells were placed along each node and collisions between the sets of cells were detected. Fig. 6 illustrates the cells placed along nodes of a wall face. To increase computation speed, each cell does not appear in the building model and exists only as a list of XYZ points. The sizes of the cells can be customized depending on the characteristics of the construction activities. After placing cells along the nodes, adjacencies between faces are examined. Fig. 7 illustrates examples of relationships between wall faces. In Fig. 7a, the right node cells of a face from wall 1 are colliding with the left node cells of a face from wall 2. If the vertical range of the colliding cells is greater than the predefined tolerance (e.g., 3 feet), the nodes are considered to be adjacent to each other. Fig. 7d illustrates top-to-bottom relationship.

Using the explained method, each node of a face is tested for its adjacency with nodes of other faces. Fig. 8 shows detailed steps of

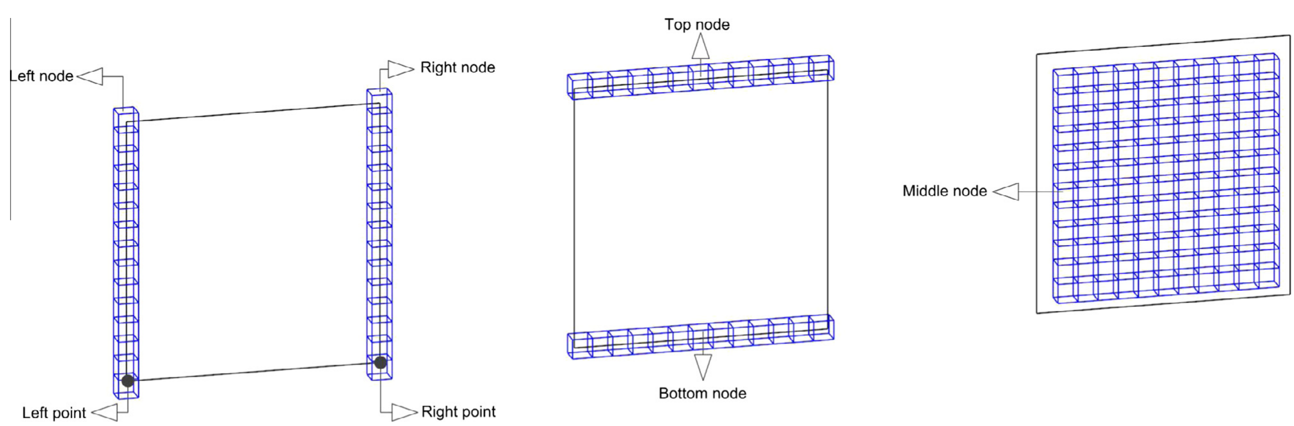

Fig. 6. Cubic cells along wall face nodes.

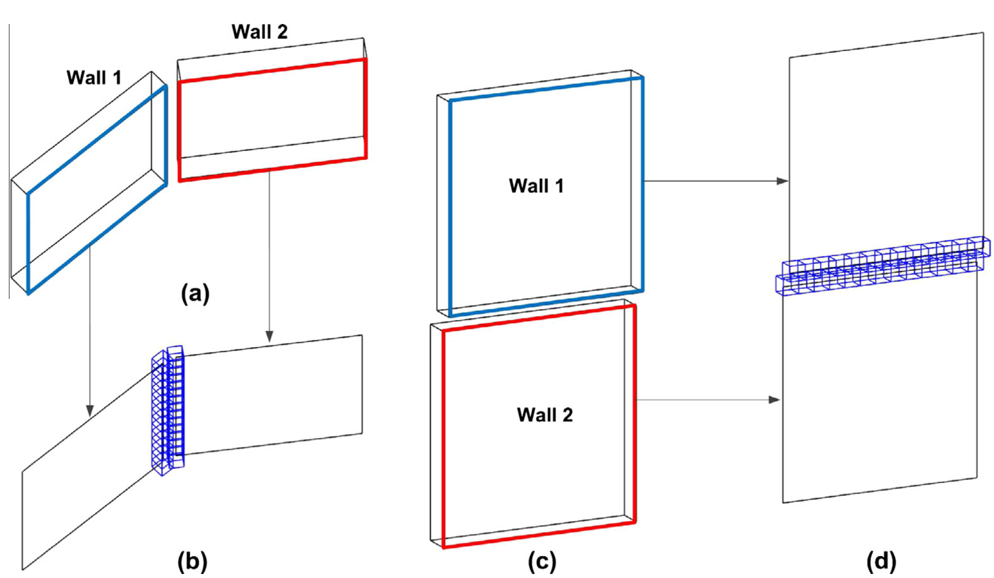

Fig. 7. Adjacency assessment based on cell collision.

```
Void wallfaceToWallfaceRelationship (Face1, Face2)
IF (Face1 and Face2 are not from the same wall)
THEN
   IF (Case 1: left-to-left)
         add Face2 to Face1's left node
         add Face1 to Face2's left node
   ELSE IF (Case 2: left-to-right)
         add Face2 to Face1's left node
         add Face1 to Face2's right node
   ELSE IF (Case 3: right-to-left)
         add Face2 to Face1's right node
         add Face1 to Face2's left node
   ELSE IF (Case 4: right-to-right)
         add Face2 to Face1's right
         add Face1 to Face2's right
   ELSE IF (Case 5: left-to-middle)
         add Face2 to Face1's left
         add Face1 to Face2's middle
   ELSE IF (Case 6: right-to-middle)
         add Face2 to Face1's right
         add Face1 to Face2's middle
   ELSE IF (Case 7: middle-to-left)
         add Face2 to Face1's middle
         add Face1 to Face2's left
   ELSE IF (Case 8: middle-to-right)
         add Face2 to Face1's middle
         add Face1 to Face2's right
   ELSE IF (Case 9: top-to-bottom)
         add Face2 to Face1's top
         add Face1 to Face2's bottom
   ELSE IF (Case 10: bottom-to-top)
         add Face2 to Face1's bottom
         add Face1 to Face2's top
   ELSE (Case 11: not adjacent)
      Faces are not adjacent
```

Fig. 8. Adjacency detection process.

detecting adjacency between two wall faces. The function *wallface ToWallfaceRelationship* receives two different faces as its arguments, checks if the two faces are originated from different wall components, and then all possible cases of adjacency relationships are tested. The nodes are filled according to the result. Only one type of relationship is applicable between two faces. For example, if the left node cells of Face1 collide with the right node cells of Face2, Face2 is added to Face1's left node and Face1 is added to Face2's right node and no other condition is tested further. In realistic models, there were several geometric conditions that satisfy multiple cases of adjacency. For example, the condition illustrated in Fig. 9 satisfies both right-to-left and middle-to-left cases if the right node cells of wall 1 face 1 and left node cells of wall 2 face 1 collide. This exception was controlled by defining an additional IF clause to left-to-left, left-to-right, right-to-right, and right-to-

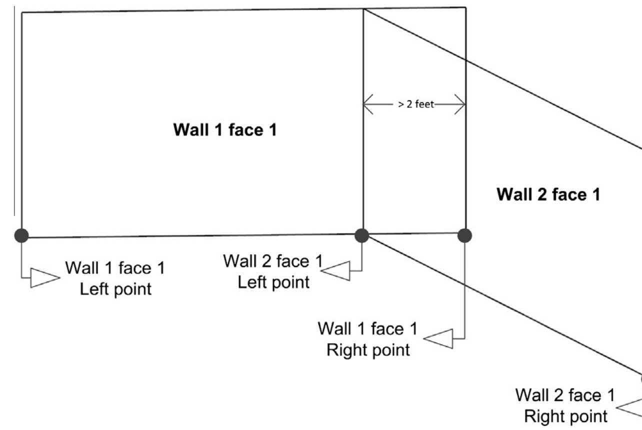

Fig. 9. A condition satisfying two adjacency cases.

left in adjacency detection process (Fig. 8). The four cases are satisfied unless a face is divided by the other face into significantly large faces. A user-defined tolerance of two feet (0.6 m) was used. According to the condition, the situation in Fig. 9 satisfies only middle-to-left case since face 1 is divided into two wall faces.

After assessing the adjacency, faces with middle faces were subdivided. In Fig. 10, the wall face has six wall faces (from three walls) in its middle node. A construction worker can easily recognize that he/she cannot continue working along wall 1 face 1 because of walls in front of it and there are four separate faces (F1, F3, F5, and F7). Even though it is easily perceivable by human's cognition, this has to be processed computationally by a computer to support automation. When faces were added to the middle node, adjacent points were recorded and used as positions dividing the face. In Fig. 10, six points (from Point 2 to Point 7) were used to divide face 1 into seven subdivided faces (F1–F7). Three subdivided faces (F2, F4, and F6) were excluded because they are not practically existing work faces. F2 was excluded by examining that both Point 2 and Point 3 are derived from the same component, Wall 2. After creating subdivided faces, the adjacency relationships are updated to substitute the original face with newly created faces. As a result, all the middle-to relationships are removed. This provides the elements that a computer program needs to generate the realistic spatial flows of a construction worker along faces.

As a result of previous process of filling adjacent faces into nodes, multiple faces can be added to each node because only adjacency is considered. In Fig. 11a, both wall 2 face1 and wall 2 face2 are added to wall 1's left node due to the adjacency. Intuitively, wall 2 face1 should be selected as the left face because a construction work cannot continue working from wall 1 face1 to wall 2 face 2. Thus, faces other than wall 2 face1 should be removed from the node. This selection was enabled by selecting the face with the smallest face-to-face angle. In this way, wall 2 face 1 can be selected because Angle 2 is smaller than Angle 1. Fig. 11b also shows a case where the angle-based selection does not yield a desired result. Intuitively, wall 2 face1 is adjacent to wall 1 face1. However, wall 3 face1 is selected if face-to-face angles are compared. To control such exception, a user-defined tolerance was used. Wall 3 face 1 divides Wall 2 face 1 into two subdivided faces. If the length of the subdivided face close to Wall 1 face is greater than the user-defined value, the subdivided face is selected. On the other hand, as in Fig. 11c, Wall 3 face 1 is selected if the face is not subdivided or the length is smaller than the value.

3.3. Adjacency graph generation and interpretation

In this step, the acquired relationship information is transformed into construction-specific spatial information. In the

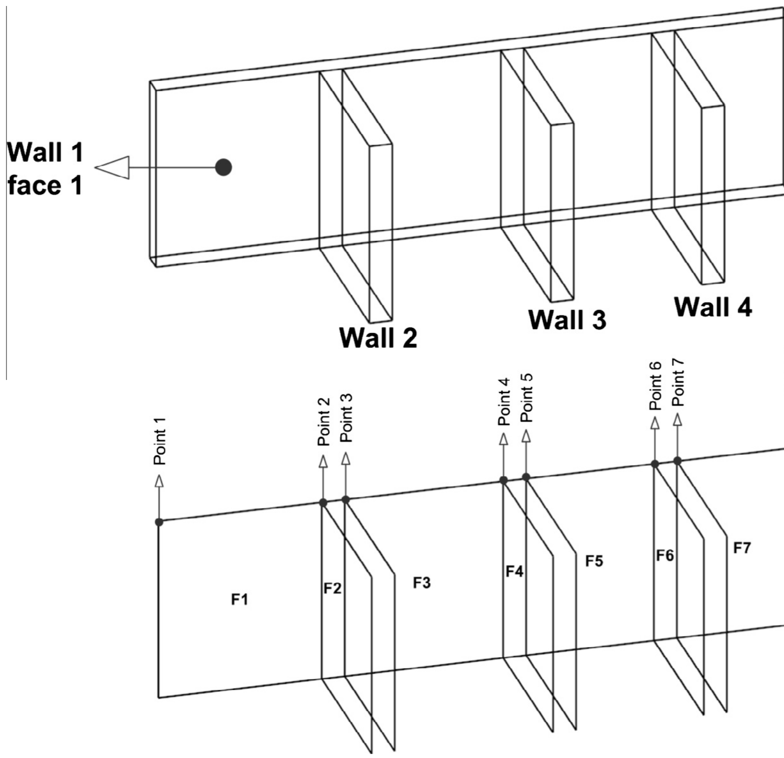

Fig. 10. A wall face divided by middle faces.

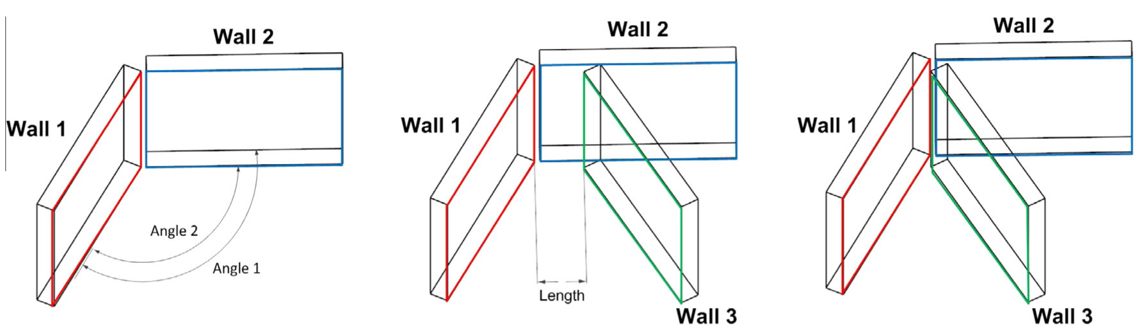

Fig. 11. Angle-based face selection and exception control.

previous steps, adjacency relationships between faces were examined and stored in the relationship data structure of each face element. Also, by dividing faces and re-arranging the adjacency relationships, each node in each face stores a pointer to a face adjacent to the node. Since this adjacency relationship between two faces shows that a construction activity can progress continuously from one face to another, work packages can be derived by linking all the adjacent faces in adjacency relationship. Fig. 12 shows (a) a part of a building model and (b) information in wall faces after they are subdivided. The graph in Fig. 13 summarizes adjacency relationships between the faces in the test model. By linking adjacent faces, five work packages were identified from the graph.

Fig. 14 illustrates identified work packages on the test model and the arrows represent surface normal vectors. As shown in Figs. 13 and 14, work package 1, 2, and 3 have closed loops while work package 4 and 5 have an open loop that forms work spaces that a construction worker can follow linearly. If a work package has a cyclic graph and all its surface normal vectors are toward inside loops' polygon, the work package was considered an enclosed space. On the other hand, surface normal vectors the cyclic graph are toward outside of the polygon, the work package was considered a continuous face forming a large work face.

After identifying work packages, spatial information related to construction can be derived. Using adjacency relationships between faces, characteristics of work packages can be analyzed. For example, different patterns of workflows can be generated for the same work package as shown in Fig. 15. Fig. 15 illustrates two work area patterns of a masonry construction activity that are applicable under the same geometric condition [36]. Exterior perimeter of a building can be detected from the adjacency graph. To be considered the exterior perimeter, work package's boundary polygon should not be bounded by any other boundary of other work packages and the work package should not be an enclosed space. Work packages forming the exterior perimeter can be detected from each floor. However, wall faces spanning multiple floors may have to be subdivided by floor slabs before the adjacency graph is generated for wall faces. After finding exterior perimeter, a spiral pattern can be generated by assigning a start point and a direction. A building face pattern can be generated by merging faces vertically.

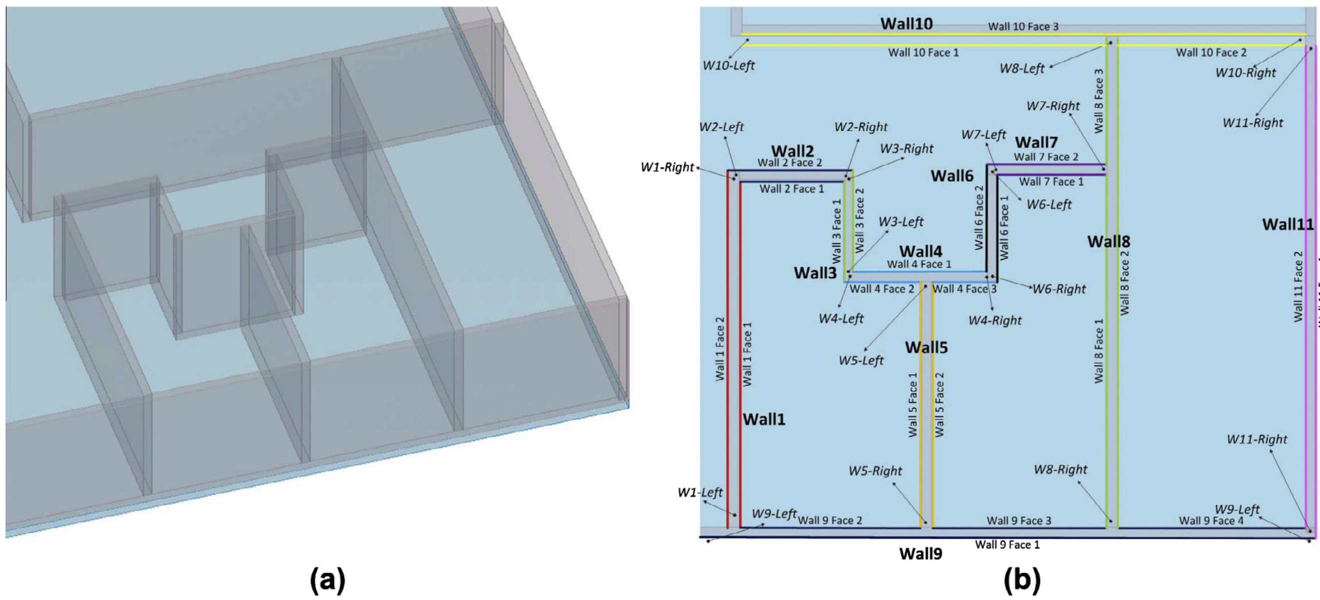

Fig. 12. A test model and face subdivision.

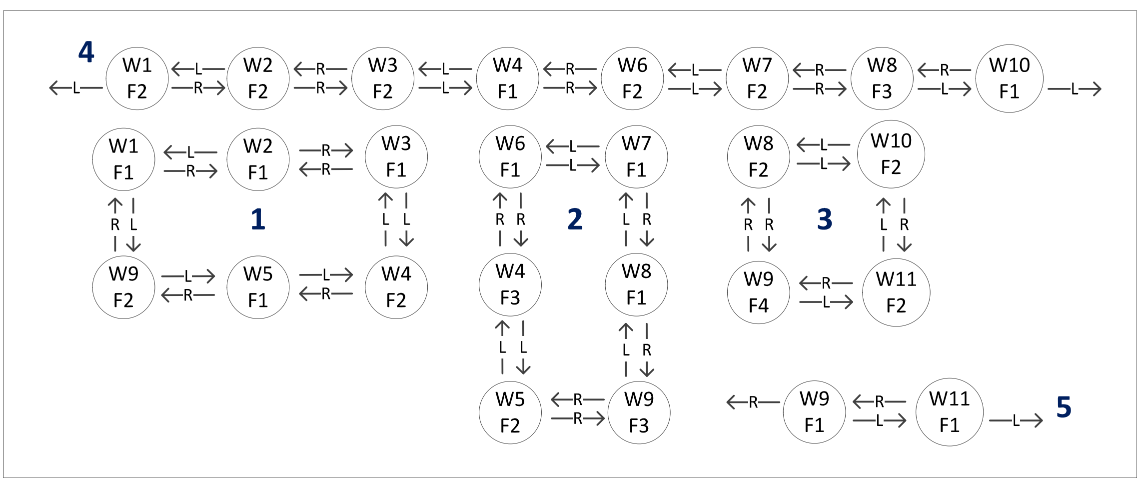

Fig. 13. Adjacency information in the test model.

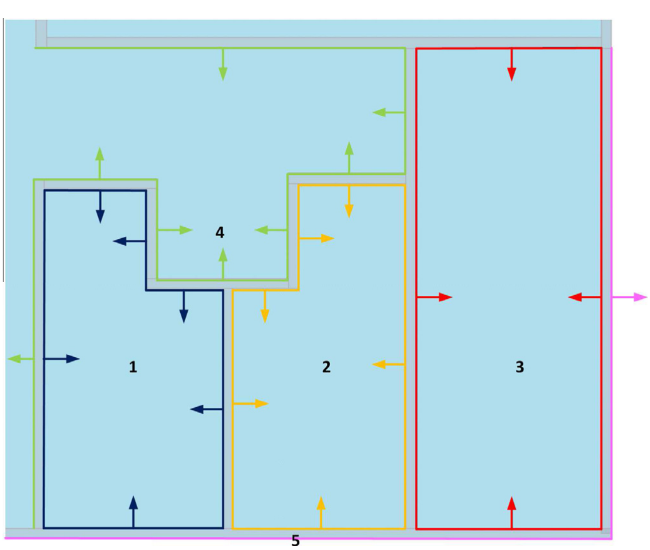

Fig. 14. Identified work packages.

This step uses information in work packages directly as the input for specific construction planning. There are many possibilities in automated planning of construction activities that use building geometric information as the input. Examples include planning of worker paths, formwork design generation, and construction safety planning. As discussed earlier in this paper, for certain construction activities, associated geometric conditions are formed by faces rather than volumes. Moon et al. [42] categorized activities into object-based and surface-based models. Activities in object-based model include concrete pouring and rebar fabrication. Drywall, paving, and ceiling grid installation are included in the surface-based model which coincides with the objective of this paper. The following case study section presents an automated analysis of ceiling grid installation activity using the proposed methods.

4. Case study and results

This section presents an implementation of CSIR in BIM and its application to assist in robust planning of selected interior con-

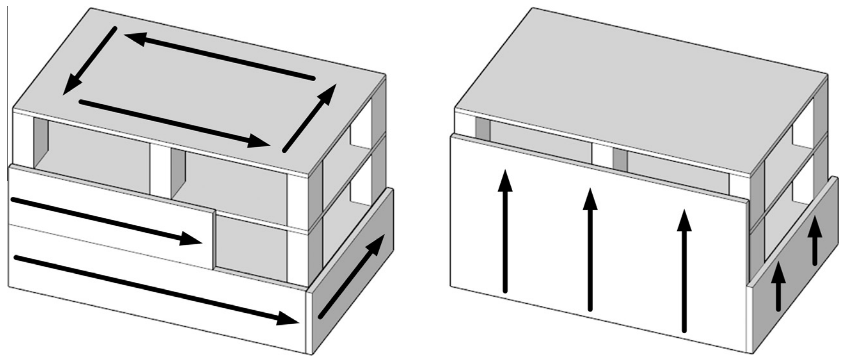

Fig. 15. Generation of construction-specific information (adapted from [36]).

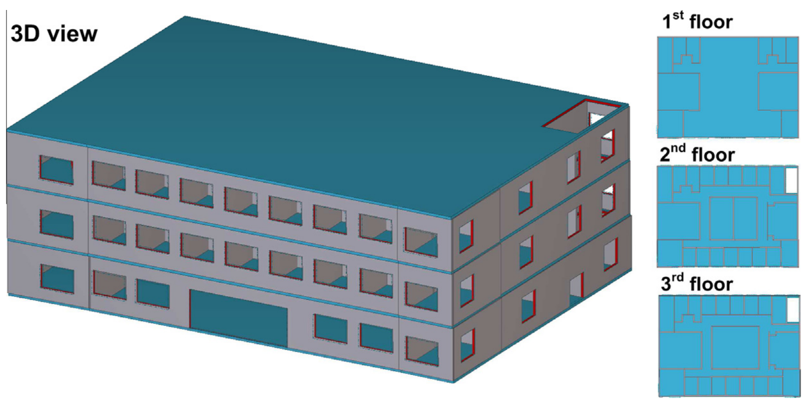

Fig. 16. A case study building model.

struction activities. A list of specific tasks and related details are discussed as follows.

- ***Programming implementation in BIM***: The proposed CSIR algorithms were programmed in one of commercially available BIM software platforms, Tekla Structures, using its API.
- ***Detecting surface-based work packages***: For selected interior construction activities, work packages formed by multiple face objects were automatically derived. (e.g., a bounded space is detected where a ceiling grid installation crew can work continuously).
- ***Defining and applying spatial characterization rules***: The spatial characteristics of the detected work packages that can impact the work productivity were automatically analyzed using predefined characterization rules. (e.g., an evaluation is conducted to check if the space is geometrically narrow and complex).
- ***Modifying original construction plan***: The implications obtained from the automated work package detection and analysis were used to refine the original construction schedule (e.g., for ceiling grid installation activities in narrow and complex areas, assumptions of lower productivity were made and the CPM schedule was adjusted accordingly).

By using the CSIR algorithms implemented in Tekla Structures, relationships between component faces were automatically assessed and work packages were detected from geometric models to assist in planning of ceiling grid construction. The BIM model for the tested building is shown in Fig. 16.

As described in previous sections, the research presented in this paper proposes an approach that enables derivation of work packages created by multiple face objects, instead of volumetric components, to create 4D BIM. In this case study, work packages for interior ceiling grid installation activity are detected by analyzing geometric relationships between wall faces constructed below the ceiling. The descriptions of related activities are as follows:

- Interior partition wall construction: This activity creates partitions that form bounded spaces within a building. The bounded spaces created during this phase do not always correspond with room boundaries in the architectural drawings since some of the partitions are constructed later. Sub-activities include framing, MEP rough-in, inspection, dry wall installation, etc.
- Ceiling construction: Sub-activities of ceiling construction include **ceiling grid installation**, MEP installation, inspection, tile installation, etc.

Accordingly, the completion of all interior partition walls forming a bounded space indicates a ceiling grid activity can be initiated for that space. Thus, even though a ceiling of a floor is often modeled as one 3D ceiling object covering the entire level, a ceiling construction activity (such as ceiling grid installation) has to be segmented into several work packages that are defined by wall faces. In this case study, CSIR will be implemented to detect available ceiling grid installation work packages and analyze construction-specific spatial conditions of each work package detected. Interviews with construction managers in interior construction were conducted to establish the rules to define the characteristics of detected work packages. Descriptions of the **characterization rules** related to ceiling grid installation are following. The numerical values were adopted based on the experience of the construction managers interviewed but they are customizable by users.

- For small or complex spaces, a work crew of two people (one installer on a scaffolding and one supporter) finishes 800 ft^2 (74.3 m^2) of ceiling grid construction in one day. A supporter hands over materials to the installer.
- For open and large spaces, a work crew of three people (two installers on scaffolding and one supporter) finishes 1600 ft^2 (148.6 m^2) of ceiling grid construction in one day. A large open space allows two installers to work together supported by one supporter.
- Spaces greater than 250 ft^2 (23.2 m^2) are considered large spaces.
- If a rectangular space is narrower than 12 ft^2 (3.65 m) in one direction, it is considered difficult to construct due to spatial congestions.
- If a space has many corners, it is time-consuming and difficult for installers to construct ceiling grids.

In this case study, the number of corners was set as ten. Then, all the work packages were detected from the case study model using CSIR. Fig. 17 illustrates work packages detected and highlighted in different colors. Work packages in the form of bounded space and continuous face were distinguished. Some of the work packages are in the form of bounded spaces and the others are in the form of continuous surfaces where construction crews can proceed unceasingly. The red thin spaces around the boundary represent exterior perimeter of each floor. Bounded spaces inside the building function as the work packages that ceiling grid installation can start. The building exterior perimeter was distinguished from other work packages computationally by identifying a work package that vertices of which are not in boundary polygons of any other work package as shown in Fig. 18. While the perimeter work packages can be used for many types of construction planning activities, such as planning of scaffolding used for exterior finishing, it is not in the scope of the presented case study.

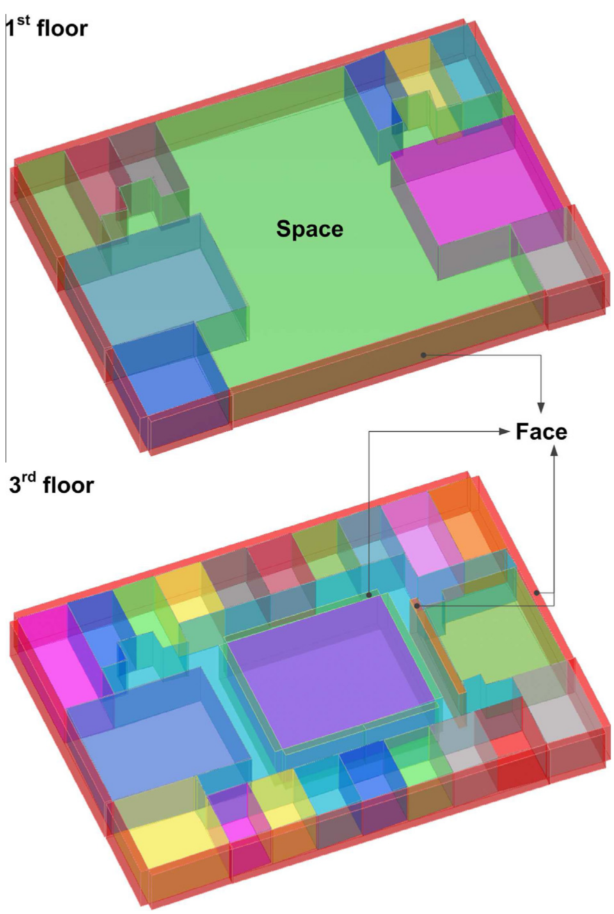

Fig. 17. All work packages detected from 3 floors.

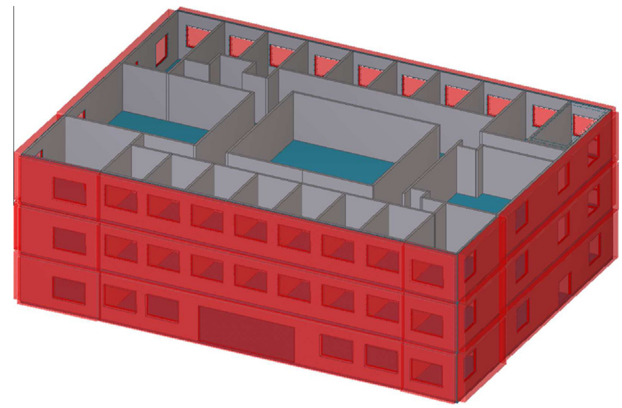

Fig. 18. Exterior work packages detected around the building perimeter.

After detecting all types of work packages, work faces in the form of bounded spaces (as shown in Fig. 19a) were analyzed. Work packages in the form of work faces were excluded since they are important for construction activities applied to wall faces, such as painting. Each space was characterized based on the characterization rules. In Fig. 19b, large open spaces, small spaces, complex spaces were colored in blue, yellow, and red,[1] respectively. In this way, ceiling grid installation activities were represented by the spaces available for the activities, instead of the entire 3D ceiling object. Also, more precise and consistent planning was possible by implementing the characterization rules that can be adjusted for different projects and planners.

Table 1 presents the proposed crew combinations and required man-hour based on the space characterization in Fig. 19b. The results in the table show varying combinations of crew sizes, associated productivity, and total man-hour required to complete ceiling grid installation for 3rd floor. Unlike the proposed approach with the result of 195 man-hours, however, the total man-hour required in the actual construction plan was computed as 215 man-hours based on a simple calculation using the total ceiling area (10,750 ft^2) with an assumed crew combination (one installer on scaffolding and an assistant) and productivity (800 ft^2/day). It is realistically challenging to consider important geometric conditions and generate detailed plans for many subcontractors' activities. Consequently, many activities are conducted solely by subcontractors without sufficient planning. Unlike the coarse estimation (215 man-hours), this approach automatically analyzed geometric information in the building model, applied construction planner's knowledge, and produced more realistic estimate (195 man-hours). As the immediate benefit, construction planners will be able to procure accurate amount of construction resources, such as installers and scaffolding, in the early planning stages without excessive manual efforts.

Finally, the results obtained by analyzing the characteristics of work packages were further used to enhance the original construction plan. Using the new productivity of the work crews to complete work packages, activity durations were recalculated. In Fig. 20, the original schedule of the construction project and the

[1] For interpretation of color in Fig. 19 and Table 1, the reader is referred to the web version of this article.

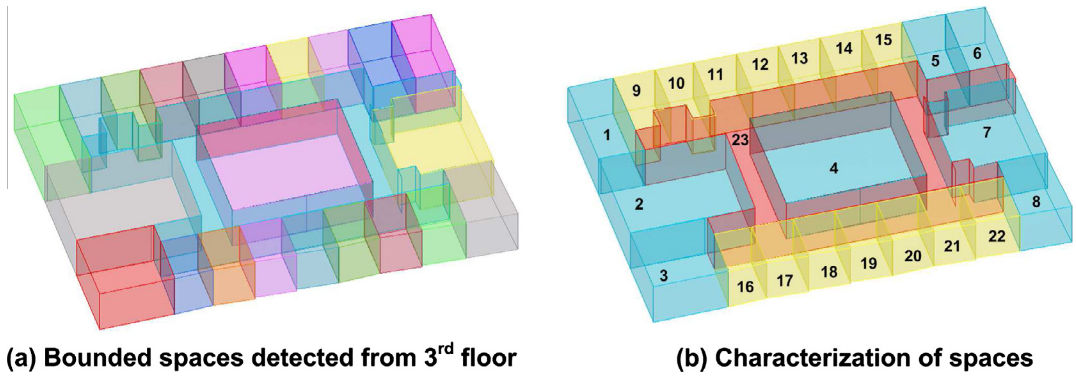

Fig. 19. Detection and characterization of bounded spaces from 3rd floor.

Table 1
Proposed crew combinations and required man-hour based on space characterization.

Work package	Characterization	Color	Work crew and productivity	Man-hour
1	Large, open	Blue	2 installers, 2 scaffolding, and 1 supporter, 1600 ft^2/day (148.6 m^2/d)	6
2	Large, open	Blue	2 installers, 2 scaffolding, and 1 supporter, 1600 ft^2/day (148.6 m^2/d)	17.4
3	Large, open	Blue	2 installers, 2 scaffolding, and 1 supporter, 1600 ft^2/day (148.6 m^2/d)	7.5
4	Large, open	Blue	2 installers, 2 scaffolding, and 1 supporter, 1600 ft^2/day (148.6 m^2/d)	21.9
5	Large, open	Blue	2 installers, 2 scaffolding, and 1 supporter, 1600 ft^2/day (148.6 m^2/d)	4.5
6	Large, open	Blue	2 installers, 2 scaffolding, and 1 supporter, 1600 ft^2/day (148.6 m^2/d)	4.5
7	Large, open	Blue	2 installers, 2 scaffolding, and 1 supporter, 1600 ft^2/day (148.6 m^2/d)	11.7
8	Large, open	Blue	2 installers, 2 scaffolding, and 1 supporter, 1600 ft^2/day (148.6 m^2/d)	10.2
9	Small, open	Yellow	1 installers, 1 scaffolding, and 1 supporter, 800 ft^2/day (74.3 m^2/d)	4.4
10	Small, open	Yellow	1 installers, 1 scaffolding, and 1 supporter, 800 ft^2/day (74.3 m^2/d)	4.4
11–22	Small, open	Yellow	1 installers, 1 scaffolding, and 1 supporter, 800 ft^2/day (74.3 m^2/d)	3.4
23	Large, complex	Red	1 installers, 1 scaffolding, and 1 supporter, 800 ft^2/day (74.3 m^2/d)	61.4
			Total	195 man-hours

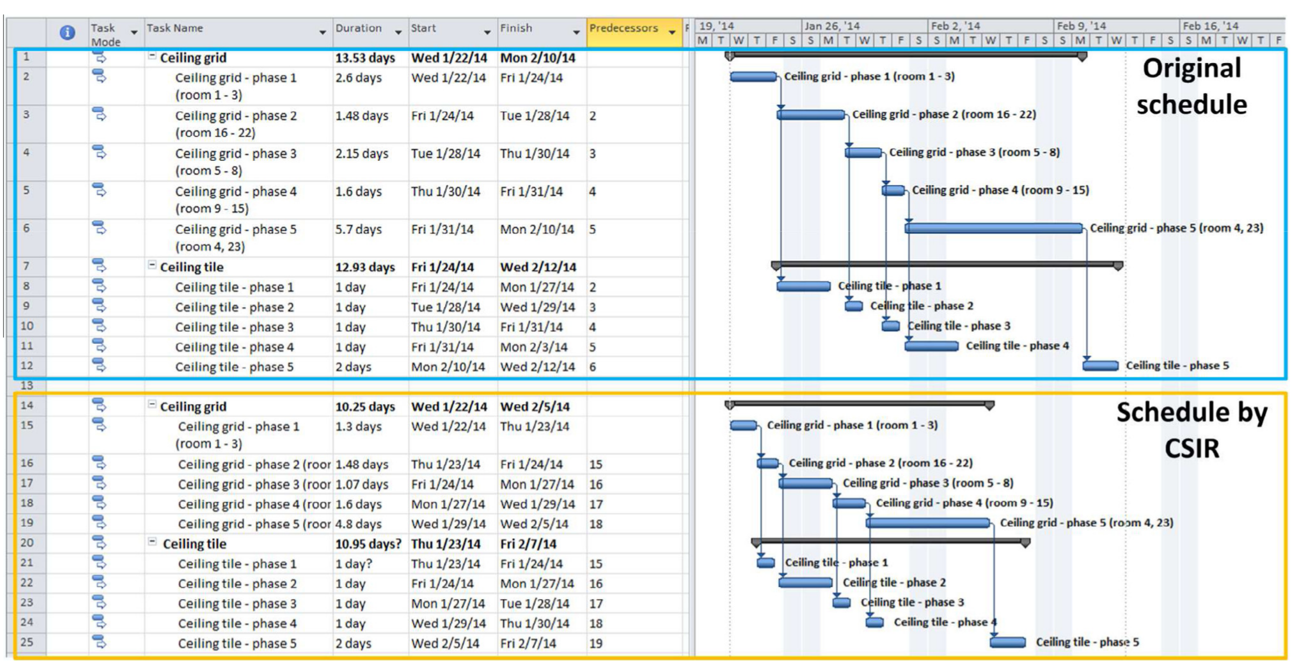

Fig. 20. Original schedule and schedule modified by CSIR results.

schedule adjusted based on newly calculated durations are compared. Since the finish dates of ceiling grid installation activities were adjusted, the start dates of succeeding tile installation activities have been updated accordingly based on the activity relationships. It implies that the tile installation crews need to come to the construction site up to five days earlier compared to the original plan. The adjusted schedule was reviewed by a construction manager who participated in the interior construction planning. In general, the construction manager agreed with the results that ceiling grid installation activities can be done in a faster pace than they were originally planned and it impacts several succeeding activities not limited to tile installation. Accurate estimation of activity durations can increase the robustness of the schedule so that work crews can better coordinate the tasks. Especially, the need for reliable schedule and coordination between crews becomes more crucial for the interior construction where there are complex interactions between multiple crews.

5. Conclusion and discussion

This paper presented a geometric reasoning system called Construction Spatial Information Reasoner (CSIR) that derives construction-specific spatial interpretation of a building model to support automated construction planning. In existing BIM-based construction planning, construction plans are generated relying heavily on construction planners' manual and subjective analyses on building geometry and construction schedule. To overcome such problems, this paper proposed an approach that automatically transforms geometric information of a building model into construction-specific spatial information that can be directly used as input for construction planning applications. Task-specific work packages are automatically derived from building design information and used in 4D BIM instead of individual building components. This feature enables automation of downstream construction planning activities and makes the proposed approach distinguishable from conventional 4D BIM and the previous work [41] that merely link solids into schedule activities. Therefore, the major contribution of this research is a seamless information flow from building product information to construction process information. Since most of construction projects are complex and involve many construction activities, automation of such geometric analysis and construction planning tasks will potentially contribute to reducing manual and mental efforts required to develop construction plans that are practical and executable. A case study is presented to demonstrate the potential of computer-assisted geometric reasoning and interpretation approach to derive useful information for a selected interior construction activity.

There are still several technical limitations to overcome. First, the proposed algorithm is applicable only to rectangle and planar surface models. To be applicable for complex construction projects, the geometric reasoning algorithms need to be improved to analyze more complex geometric conditions. In addition, the geometric analysis algorithms can be greatly improved by using room or zone information available from architectural models. If an architect assigns a room tag, it can provide additional information such as the room's location and components constituting the room geometry. This can significantly reduce the computational complexity of adjacency detection algorithm (Fig. 8) and the need to control exceptions. However, in this paper, the algorithms were developed without the room information since dynamically changing geometric conditions have to be analyzed where rooms may not be constructed at a certain point of construction.

Second, different rule sets are needed to apply the proposed approach to different activities. As a limited scope of the study, we established a set of characterization rules that is used to evaluate geometric conditions specifically for ceiling grid installation. Considering the fact that there are several construction activities that are impacted differently by the same geometric condition, a more scalable algorithm needs to be designed.

Third, conditions other than structural components (such as walls and slabs) were not considered as part of the automated assessment. For example, the productivity of ceiling tile installation activities can be greatly impacted by the complexity of electrical systems in the spaces. Although our research in this paper did not address this need, including such aspects to the characterization rules would make the assessment more realistic.

Further research can be proposed to improve characterization of work packages. While this research adopted a deterministic approach to characterization of work packages from the viewpoint of a construction activity, development of probabilistic approaches of analyzing work package information would be required since preparing and programming all the required geometric rules for characterization can be unrealistic. Also, research can be proposed on automatically planning construction activities of various space use patterns presented in [36] such as a spiral pattern of building exterior. In case of construction of discrete building components, such as concrete columns, a different algorithm should be developed to propose an optimal sequence of construction. In those cases, relationships other than face adjacency have to be used to analyze geometric condition. Since construction productivity and safety can be influenced by how construction activities of different characteristics are planned, future research may also focus on generating spatial flows of multiple construction activities of different spatial characteristics and further optimizing the generated spatial flows to minimize risks like spatial conflicts.

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