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Elemental Graph Data Model: A Semantic and Topological Representation of Building Elements

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***Abstract*—**With the rapid increase of complexity in the building industry, professionals in the A/E/C industry were forced to adopt Building Information Modeling (BIM) in order to enhance the communication between the different project stakeholders throughout the project life cycle and create a semantic object-oriented building model that can support geometric-topological analysis of building elements during design and construction. This paper presents a model that extracts topological relationships and geometrical properties of building elements from an existing fully designed BIM, and maps this information into a directed acyclic Elemental Graph Data Model (EGDM). The model incorporates BIM-based search algorithms for automatic deduction of geometrical data and topological relationships for each building element type. Using graph search algorithms, such as Depth First Search (DFS) and topological sortings, all possible construction sequences can be generated and compared against production and construction rules to generate an optimized construction sequence and its associated schedule. The model is implemented in a C# platform.

***Keywords*—**Building information modeling, elemental graph data model, geometric and topological data models, and graph theory.

I. INTRODUCTION

OVER the past 100 years, the building industry has changed dramatically. Buildings have become much more complex with many interconnected and integrated systems. Project managers are faced with complex decision environments and problems in the construction of the majority of the projects. For project managers to take sound decisions, they just rely on human value and judgment systems which contribute to the project problems as well. Therefore, it would be beneficial to aid project managers in order to make sound decisions regarding the intelligent knowledgeable selection of the optimal construction methodology.

This complexity has forced the designers in the A/E/C industry to consider more inputs in their design analysis. With the added complications, owners, designers and contractors had to adapt to these changes and take into consideration more factors in order to keep up with the continuously growing industry. To analyze these factors in a proper manner where all communication requirements are met, professionals in the A/E/C industry began searching for better ways to model facilities/buildings and coordinate all this information together between all the involved parties throughout the project's life cycle [1]. These efforts were harmonized with research in the field of computer-supported building design, and, consequently, led to the continuous advancement in the development of building data models.

A. Building Data Model

Building data model describes the physical characteristics of building elements by means of their three-dimensional (3D) geometry and topology. Geometric data represent the building element's dimensions and location, whereas topological information represents spatial relationships among the building elements comprising connection, adjacency, containment, separation, and intersection [2].

Project participants/stakeholders consider topological information essential to perform various analyses during design and construction. For example, structural engineers require information about connections between individual structural elements to be able to conduct the structural performance analysis or constructability evaluation, whereas architects require the adjacency and intersection between building spaces and their boundaries to plan layout and create functional space. MEP engineers, however, utilize the topological relationships between building elements, as well as spaces and their enclosing structures, to check compliance with building codes, for instance, sunlight analysis, heat-loss calculations, thermal analysis, and building energy optimization. Moreover, construction planners need topological and relationship information to determine the vicinity among construction zones in layout planning, and, hence, establish the interdependencies of construction activities to be performed [2]. For such complex tasks to be performed with the aid of building data models, advanced ways of extracting and presenting geometric and topological information should be adopted [3].

While geometric data of building elements can be manipulated and managed by a Computer-Aided Design (CAD) interface, their topological information are conventionally inserted into the model. However, the manual data representation is essentially a complex and challenging task as each constructed facility usually comprises of hundreds of elements with multiple types of topological and relationship information, such as connectivity, adjacency, containment, and intersection [2].

The current lack of such building models that support geometric-topological analysis resulted in various research attempts in the field of computer-based representation of

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building elements over the last decade. These efforts have concentrated mainly on the development of a semantic object-oriented building model, also called Building Product Model or BIM [4].

B. BIM

BIM is a revolutionary technology which has transformed and promoted how buildings are designed, analyzed, constructed and managed [5]. It was introduced to distinguish the information rich 3D modeling from the traditional 2D drawing, and is becoming a better known established collaboration process in the construction industry. BIM is simply a building design methodology characterized by the creation and use of coordinated, internally consistent computable information about a building project in design and construction [5].

General Services Administration (GSA) of the United States government defines BIM as: “Building Information Modeling is the development and use of a multi-faceted computer software data model not to only document a building design, but to simulate the construction and operation of a new capital facility or a recapitalized (modernized) facility. The resulting Building Information Model is a data-rich, object-based, intelligent and parametric digital representation of the facility, from which views appropriate to various users’ needs can be extracted and analyzed to generate feedback and improvement of the facility design” [6]. According to the National Institute of Building Sciences (NIBS), it is best to think of BIM as: "A digital representation of physical and functional characteristics of a facility. As such it serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its lifecycle from inception onward” [7].

Moreover, BIM Model is made of intelligent building components along with their data attributes and parametric rules (e.g. doors are parametrically related and hosted by a wall). In addition, BIM provides consistent and coordinated views of the data model, which saves designer’s time as each view is internally coordinated through the built-in intelligence of the model. Hence, BIM is a great platform in order to share knowledge and communicate between the project’s participants [7].

C. BIM and its Implementation in the Construction Industry

The main benefits of BIM for construction professionals include but not limited to: visualization, 3D coordination, construction planning and monitoring, and quantity take offs. Project savings are considerably high if BIM is utilized in the early design phase, as this will save a lot of the coordination efforts and, hence, considerably reduces trade conflicts.

BIM opportunities that are currently being leveraged and explored by construction companies are staggered. As BIM becomes more widely adopted, information on buildings will increasingly be recorded in models, which can then be utilized for other purposes. [8]

II. CURRENT PRACTICES/PROBLEMS IN THE CONSTRUCTION INDUSTRY

Most BIM users today are still in the first phase of BIM utilization: utilizing BIM for visualization and documentation. Data-driven analysis, the second phase, is currently being explored and is yet not smoothly integrated. The last phase of BIM utilization is simulations. In this phase, the BIM model is utilized to imitate the characteristics of the construction project, for optimization, engineering, and testing [9]. Hence, BIM not only helps in better visualization and documentation, but is also a catalyst for an enhanced and improved process in the design and construction industry. BIM models usage fused with modeling, and simulation tools allow efficiently prototyping a building and examining its construction activities before breaking the ground. Such prototyping holds a lot of value, as it implores designers to avoid fudging practices, hence, improving quality and productivity while bringing out best practices [9].

To harvest BIM’s true value, attempts to develop models that can support geometric-topological analysis of building elements are currently being explored.

III. TOPOLOGICAL DATA MODELS

Literature review has indicated that there are several existing models to represent geometric data and topological relationships among building elements through topological primitives [4], [10]-[19]. However, these models are inadequate to handle various queries and complex network analysis. Most of these models store limited semantic information about rooms, openings and walls. Furthermore, such models only deal with connectivity and adjacency neglecting any other type of topological relationship. However, BIM demands the availability of all the types of relationships (e.g. connectivity, and containment) and their effectively storage, in order to enhance the performance of spatial analysis such as construction sequencing, 5D simulation, energy simulation, emergency response and prefabrication optimization [3].

IV. RESEARCH OBJECTIVE

Consequently, BIM should be utilized to develop a reliable model to perform geometric-topological analysis of building elements that can support all types of spatial relationships. And, hence, aid professionals in the A/E/C industry to make sound decisions regarding the selection of the optimal construction methodology in order to obtain better cost and time trade-off.

For this purpose, an intelligent framework with advanced computational tools and algorithms is designed and created to achieve a higher degree of design-construction integration and spatial integration of individual building elements in order to achieve an optimized coordinated construction plan. This could be accomplished by obtaining the optimal sequencing of building elements (in terms of time and cost), and, accordingly, recommend the Optimized Elemental Construction Method, Schedule & Resources, and, hence, generate 4D and 5D BIM models. The framework is, then, validated with the aid of a set of automatically generated test cases in order to assess the research findings. Since graphs are highly versatile models for analyzing a wide range of practical problems in which points and connections between them have some physical or conceptual interpretation, graph theory is used to represent the building elements and their relationships.

The framework is designed based on a three-level concept, namely: Elemental Graph, Inter-Elemental, and Entra-Elemental.

1. Elemental Graph – In this level, all the BIM Model building elements are mapped into a set of vertices and their interrelationships are converted into a set of edges, thus, forming a directed acyclic EGDM, as shown in Fig. 1.
2. Inter-Elemental – In this level, each element type can be built with a set of construction methods, as shown in Fig. 2. By electing an appropriate construction method for each building element, the Elemental Construction Method Graph is formed.
3. Entra-Elemental – In this level, customized user-defined relationships are introduced to mimic any practical constraints, as shown in Fig. 3.

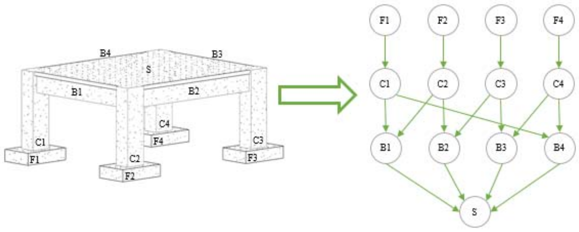


Fig. 1 Level (1): Elemental Graph

This paper focuses on the first level of the framework, Level (1): Elemental Graph.

A novel EGDM is proposed in this research to abstract and represent building elements and their relationships in a graph in which vertices denote building elements; while edges represent the topological relations. The EGDM is enhanced by adding semantic information to the vertices to be able to handle wide ranges of queries. Furthermore, a novel BIM-based algorithm is proposed to deduce the topological relationships among building elements.

V. PROPOSED MODEL

This section presents the proposed model for extracting all building elements' topological relationships and geometrical properties from an existing fully designed BIM Model. The information is then presented in a directed acyclic EGDM, in which vertices denote building elements; while edges represent the topological relations. The EGDM is enhanced by adding semantic information to the vertices to be able to handle wide ranges of queries. Furthermore, a novel BIM-based algorithm is proposed to automatically deduce the topological relationships among building elements. The model is implemented in a C# platform.

N.B. The EGDM, representing topological relationships and semantic information of building elements in micro-spatial environments, is considered a base for the next two (2) levels, where it is utilized using graph search algorithms, such as DFS and topological sortings, to obtain all possible construction sequences and, hence, recommend the Optimized Elemental Construction Method.

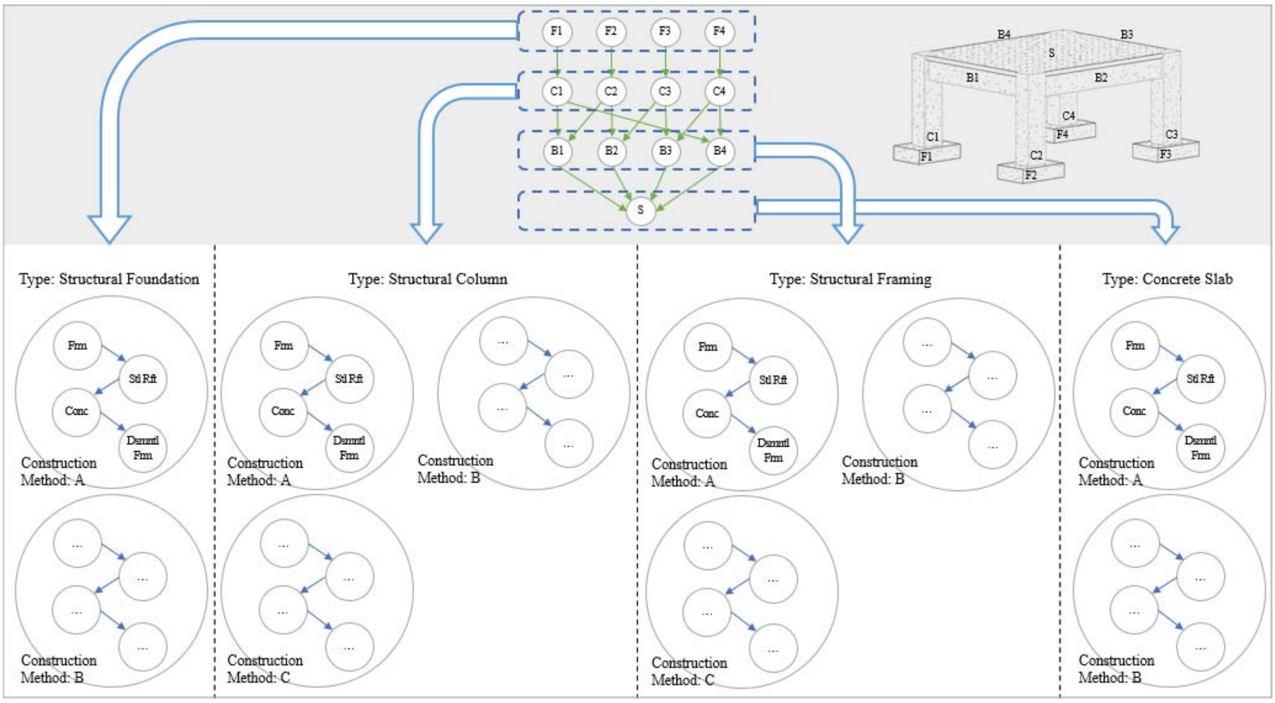


Fig. 2 Level (2): Inter-Elemental

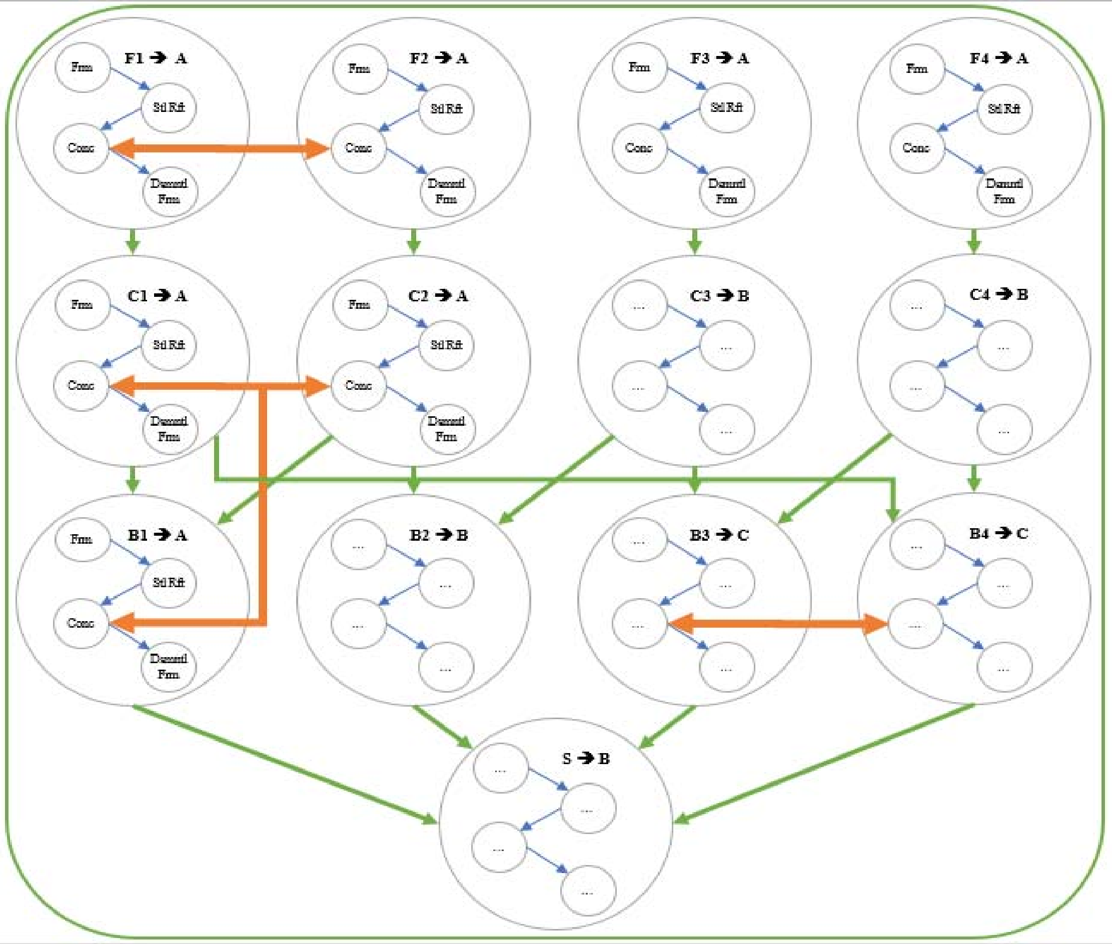


Fig. 3 Level (3): Entra-Elemental

A. Proposed Framework for Deriving the EGDM

Fig. 4 shows the EGDM proposed architecture that derives the Elemental Graph with the aid of EGDM basic elements and the building elements' topological/geometric representations. The EGDM comprises two main modules, namely:

1. Project Analysis
2. Elemental Graph Retrieval

In the first module: Project Analysis, building elements are extracted from the Project BIM Model.

In the second module: EGDM Retrieval, building elements' properties and spatial relationships are deduced from the BIM Model in order to generate the EGDM.

1. Project Analysis Module

Essentially, the Project Analysis Module, as shown in Fig. 4, is the first unit in EGDM that, with the aid of the Analyzer, parses the input data acquired from the Information Feeder (General Information and Project's BIM Model), and, then, builds an internal data structure to release Element(s) Data that would provide easy data access for its receptor, the EGDM Retrieval Module.

The process starts with the Information Feeder in which the user feeds in General Information about the project along with the Project's fully designed BIM Model.

Next, the Analyzer imports building elements data, including topology/geometry properties, dimensions, materials, and functionality, from the BIM Model into the framework. It, then, builds an internal data structure to map the data obtained into the memory. The data structure is a linked list, comprising a list for each building element which gets linked together. Each building element's list carries the retrieved semantic data for that element including: category, center-point, faces, ID, length, level, materials, max point, min point, etc… It is worth mentioning that this list gets further extended and lengthened throughout the following module to include additional imported and calculated data. This process finally categorizes and segregates all the building elements based on their element category to release the Element(s) Data that would serve as an input for the following module.

2. EGDM Retrieval Module

The EGDM Retrieval Module, as shown in Fig. 4, is a functional unit in the EGDM that transposes the geometry and topological relationships of building elements, Element(s) Data, obtained from the Project Analysis Module to a graph model, EGDM. This module, with the aid of the Spatial

Relationships Extraction and Building Elements Properties Extraction, automatically deduces the geometric and topological information for all the building elements. Building elements along with their relationships and semantic data are mapped into a novel data representation model: directed acyclic EGDM.

The process starts with the Create EGDM Vertices in which the retrieved building elements in the Element(s) Data gets represented as vertices in the EGDM.

The Spatial Relationships Extraction employs a "topology–driven" approach that further examines the project's building elements. It, firstly, checks for building elements' predefined relationships, and, thereafter, creates bounding boxes around building elements in order to automatically deduce the topological relationships among them, as described in following sections. Hence, locating the building elements and their respective dependencies to form the Building Elements' Adjacency Matrix, which are, then, represented as directed edges with the aid of Create EGDM Edges in the directed acyclic EGDM.

Next, the Building Elements Properties Extraction obtains the geometric data for each building element from the Element(s) Data, and, calculates its relevant properties by the Additional Properties Computation. These properties are, then, added to each building element's associated Semantic Data Table (SDT) with the aid of Add SDT to EGDM Vertices.

By the end of this process, the outcome is the Elemental Graph of the project under study, EGDM, which could be used to generate an optimized construction sequence and its associated schedule.

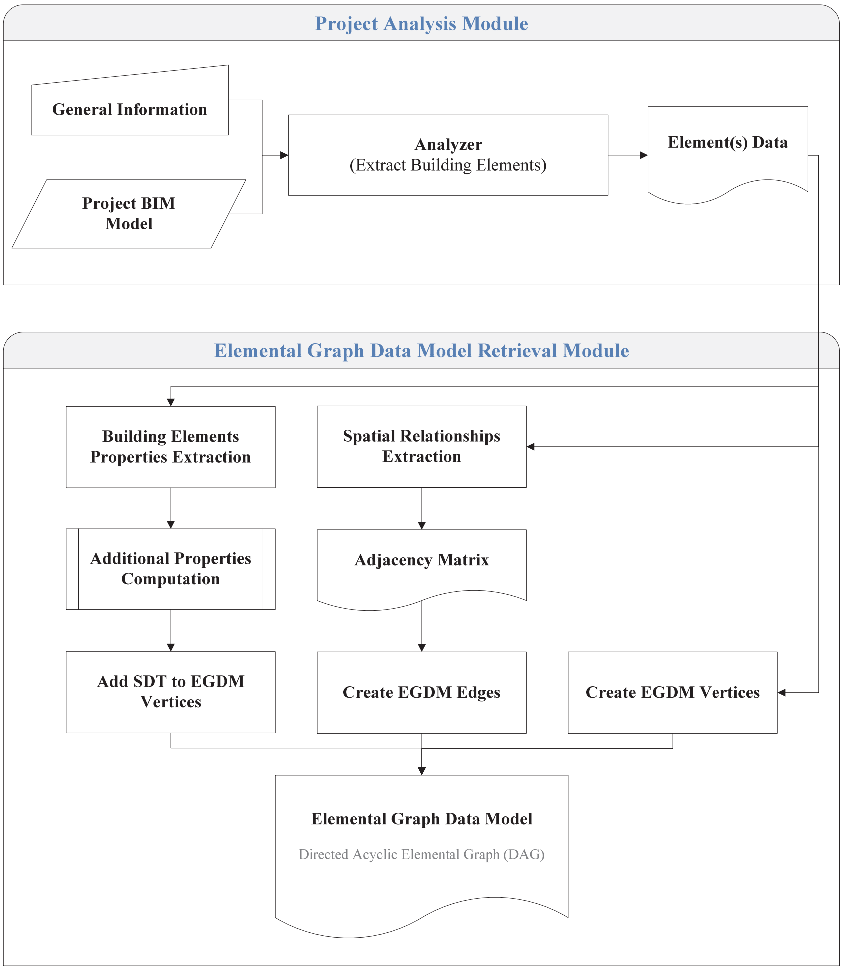


Fig. 4 Proposed Framework for EGDM

B. Elements of the Proposed Model

Performing geometric-topological analysis of building elements, that would aid professionals in the A/E/C industry in selecting the optimal construction methodology, is very difficult and in most cases impossible without the existence of a semantically rich representation of the building elements: a simple graph. Graphs are highly versatile models for analyzing a wide range of practical problems in which points (nodes or vertices) and connections (links or edges) between them have some physical or conceptual interpretation. Modeling real-world problems ranging from geographic adjacency (vertices: City/State, and edges: borders shared), Inter-state roads network (vertices: States, and edges: roads), Ecosystem – Food Web (vertices: Species, and edges: Predator – Prey), and

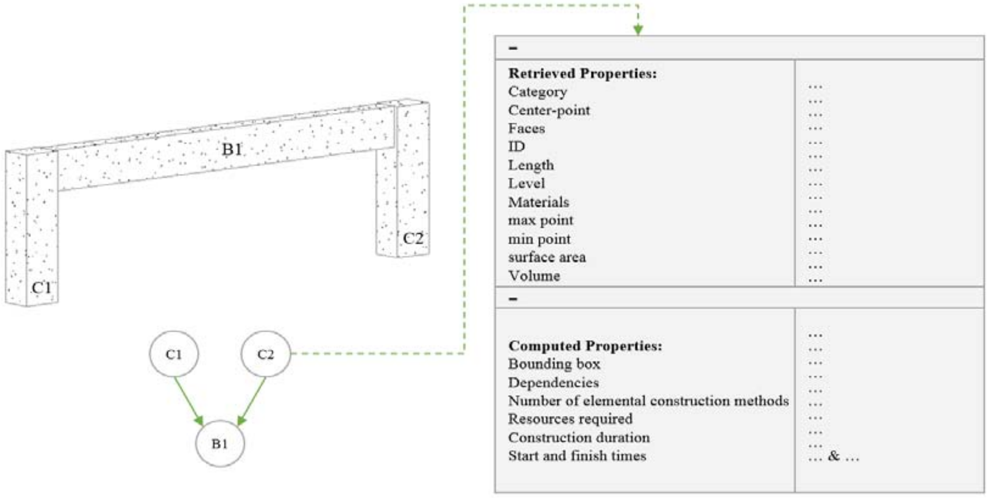
Recursive Software Systems (vertices: Functions, and edges: Function Calls), require different kinds of graphs. Depending on the complexity of the application, the appropriate kind of graph is employed and advanced graph algorithms, such as spanning trees, shortest path, Hamiltonian paths, search algorithms and topological sortings, are utilized, resulting in a significant reduction in the computational time and storage as compared to dealing with the real-world application directly.

The proposed model abstracts and represents building elements and their relationships in a simple directed (all the edges are directed) acyclic (graph has no cycles or loops) graph, the EGDM.

The EGDM is composed of three main elements, namely: vertices, edges, and semantic data table (SDT). In the EGDM's graph structure, vertices represent building elements, and directed edges represent topological relations, whose direction identifies the interrelationships between the respective building elements and allow for assigning customized relationships that would mimic any practical constraints in a later stage: Level 3. This simple directed acyclic graph is a logical network data model that can be utilized to handle graph search algorithms, such as Breadth First Search (BFS), DFS and topological sortings, to obtain all possible construction sequences. The building elements' semantic information required for such algorithms and a wide range of queries, are attached to their respective vertices by a data table, the semantic data table (SDT), which is the third element of the EGDM.

1. Graph Data Structure

The graph data structure is a definition for building elements from a specific group that are topologically related. In order to build the EGDM, a vertex is assigned for each building element, and paired vertices are joined with an edge on the condition that the corresponding building elements are interrelated. A beam and two (2) columns, as shown in Fig. 5, are mapped into vertices B1, C1, and C2 in the EGDM. Since the beam B1 is supported on the two (2) columns C1 and C2, two (2) directed edges are mapped from the columns C1 & C2 (tails) to the beam B1 (head) respectively to denote the elemental dependencies between the elements.



–	
Retrieved Properties:	…
Category	…
Center-point	…
Faces	…
ID	…
Length	…
Level	…
Materials	…
max point	…
min point	…
surface area	…
Volume	…
–	
	…
Computed Properties:	…
Bounding box	…
Dependencies	…
Number of elemental construction methods	…
Resources required	…
Construction duration	…
Start and finish times	… & …

Fig. 5 Mapping building elements to a directed acyclic EGDM

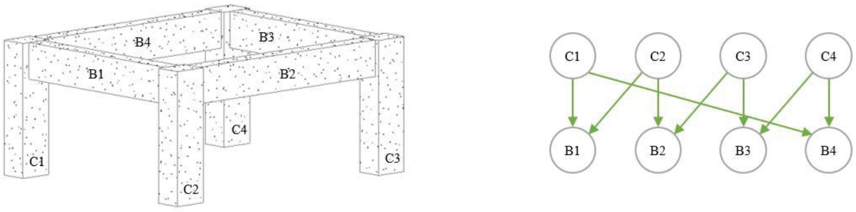


Fig. 6 Example No. 1 and its Elemental Graph (4 columns and 4 beams)

For an entire building, the EGDM defines the spatial relationships of its building elements. The types of topological relationships are represented through the direction of the edges, whereas the building elements' properties are included in the semantic data table (SDT), which are labels assigned to the associated vertices. Upon retrieval of all the building elements' properties, additional computed ones are added to the semantic data table (SDT) of each building element respectively, as shown in Fig. 5.

A demonstration for the building-to-graph generation is shown in Fig. 6 andFig. 7. Fig. 6 shows an example of a simple concrete structure composed of four (4) columns and four (4) beams, which is represented as a directed acyclic graph (DAG) composed of eight (8) vertices and eight (8) edges. Fig. 7 shows an example of a simple concrete structure composed of four (4) foundations, eight (8) columns, eight (8) beams, two (2) slabs, four (4) walls, a door and a window, which is represented as a directed acyclic graph (DAG) composed of twenty-eight (28) vertices and thirty-eight (38) edges.

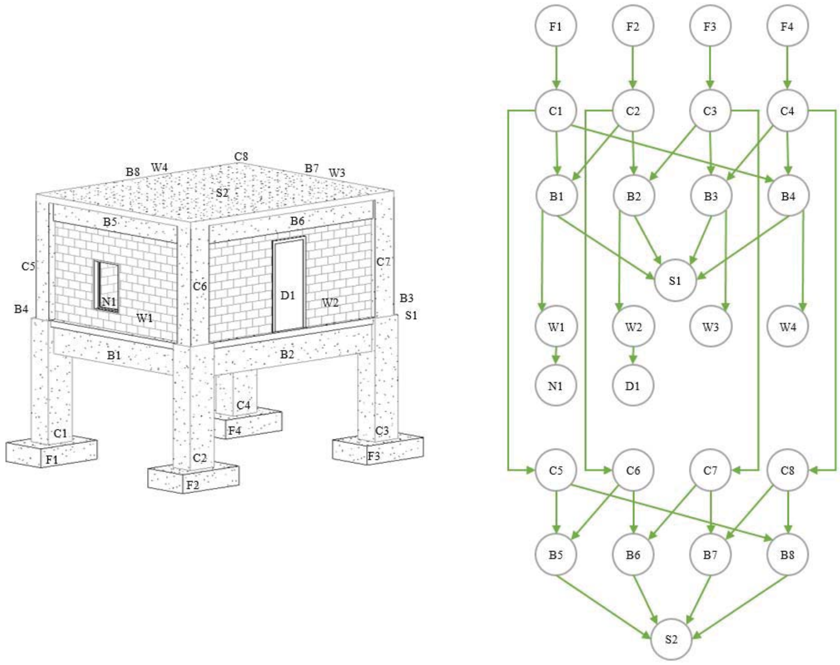


Fig. 7 Example No. 2 and its Elemental Graph (4 foundations, 8 columns, 8 beams, 2 slabs, 4 walls, door, and window)

The graph data structure in its presentation preserves the physical and topological characteristics of building elements, as well as the topological consistency through mapping all the building elements along with their topological relationships into a set of vertices and edges.

2. Graph Theory and Adjacency Matrix Notations

Graph theory can be used to represent topological relationships in any graph G through the stipulation of sets of edges and vertices, namely E and V respectively.

Since most of the building projects comprise of a relatively large number of vertices, line drawings are no more adequate for describing the EGDM, hence, another more formal kind of specification of the EGDM is needed. A directed acyclic graph can be defined by a list of its vertices V, a list of its edges E, and a two-row incidence table whose columns represent the edges and rows represent the vertices (head and tail). Each edge is defined with a pair of vertices (v, v^h), where $v, v^h \in V$. The head vertex v^h is marked to designate it from the tail v. For instance, the example in Fig. 6 can be represented as:

TABLE I
The Example of Fig. 6

edge	e1	e2	e3	e4	e5	e6	e7	e8
endpoint 1	C1	C1	C2	C2	C3	C3	C4	C4
endpoint 2	$B1^h$	$B4^h$	$B1^h$	$B2^h$	$B2^h$	$B3^h$	$B3^h$	$B4^h$

The Elemental Graph can also be stored in the form of a matrix to facilitate computational analysis and storage purposes. The matrix is often referred to as the Adjacency Matrix (Adj). For any structure composed of N building elements, the dimensions of its adjacency matrix is N x N, and Adj is represented in (1) as shown below:

$$Adj_{DAG}\,[v, v_h] = \begin{cases} 1 & \text{if there is an edge from } v \text{ and } v_h \\ 0 & \text{otherwise} \end{cases} \qquad (1)$$

3. Semantic Data Table (SDT)

Upon the retrieval of the logical EGDM based on the spatial relationships among building elements of a facility, building elements' properties, such as: category, center-point, faces, ID, length, level, materials, max point, min point, surface area, volume, etc…, are included in the semantic data table (SDT), which are assigned to the associated vertices. Upon retrieval of all the building elements' properties, additional computed ones are added to the semantic data table (SDT) of each building element respectively, as shown in Fig. 5. These properties include: bounding box, dependencies, number of elemental construction methods, resources required, construction duration, start and finish times, etc …

With the aid of the building elements' semantic data table (SDT), the EGDM can handle a wide variety of queries and search algorithms, such as Breadth First Search (BFS), DFS and topological sortings, to obtain all possible construction sequences.

C. Extraction of Topological and Geometric Data

The BIM data structure is a semantically rich environment explicitly representing both topological and geometric information, along with non-geometric properties (e.g., material properties). To extract topological and geometric information, various research attempts in the field of Information Technology is and was undertaken to ensure a continuous flow of the required information from BIM Models. AutoDesk Revit, being a design and documentation platform that supports the design, drawings, and schedules required for BIM [20], facilitated the smooth extraction and exchange of data between BIM Models and applications, hence, avoiding the time-consuming and error-prone process of obtaining and sharing such data. Data extraction is carried out using the AutoDesk Revit SDK and AutoDesk Revit APIs to communicate with AutoDesk Revit. AutoDesk Revit customization capabilities have been significantly extended over the past few years. AutoDesk Revit Application Programming Interface (API) allows users to program with any .NET compliant language such as VB .NET and C# .NET. With the AutoDesk Revit APIs, it is now possible to extract topological, geometric, and semantic information of building elements to complete the proposed EGDM.

D. Topological/Geometric Representation of Building Elements in AutoDesk Revit

AutoDesk Revit API is used to facilitate the implementation of the EGDM's topology-driven approach in deducing topological relationships by providing the required topological features, as well as predefined topological relationships in its hierarchical structure.

1. Representation

Families are considered as the basic elements of Autodesk Revit platform where almost every object is based on a family definition. The family holds the geometric definition of the element and the parameters used by the element. Families, such as structural columns, structural framings, slabs, walls, windows, stairs, doors, etc., are used to build the BIM. Each family can have multiple types, such as different size, materials, parameter variables, etc. Any change to a type is updated in every instance throughout the project.

Basically, each building element in the AutoDesk Revit BIM Model has a geometric/topologic representation. And each element category is modeled and represented in a distinct manner. For instance, structural columns, structural foundations, doors and windows are typically characterized by their "Location Point", while structural framing and walls are typically characterized by their "Location Curve". Fig. 8 illustrates the structural column and structural framing representations along with the retrieved minimum and maximum points which will be utilized in the following section.

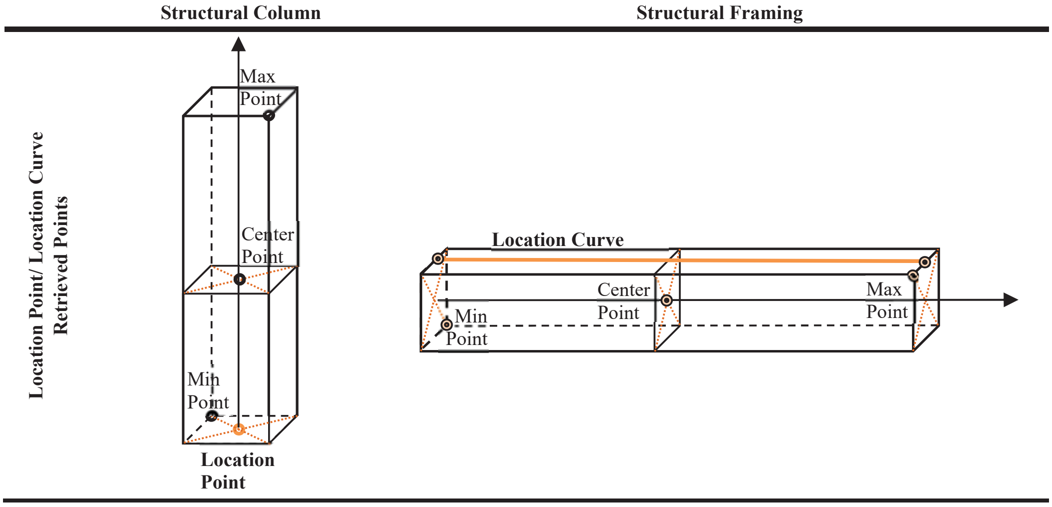


Fig. 8 Structural Column and Structural Framing Representation

2. Obtaining Minimum and Maximum Points

In order to create the bounding box, two (2) points, minimum and maximum points, should be identified with the aid of building element's geometry and the LocationPoint/LocationCurve. These two (2) points are simply computed and added to the building element's semantic data table (SDT) respectively.

In case of inclined building elements in one plane, minimum and maximum points can be computed in the element's local coordinates and transforming these coordinates to the Global Coordinates System through 2D Cartesian Coordinate Systems Transformation as indicated in (2):

$$\begin{bmatrix}X\\Y\end{bmatrix} = \begin{bmatrix}X_{translation}\\Y_{translation}\end{bmatrix} + \begin{bmatrix}\cos\theta & -\sin\theta\\ \sin\theta & \cos\theta\end{bmatrix}\begin{bmatrix}x_1\\y_1\end{bmatrix} \qquad (2)$$

where the angle θ resembles the angle of rotation about the x-axis. In case of inclined building elements in 3D, minimum and maximum points can be computed in the element's local coordinates and transforming these coordinates to the Global

Coordinates System through 3D Cartesian Coordinate Systems Transformation as indicated in (3):

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} X_{translation} \\ Y_{translation} \\ Z_{translation} \end{bmatrix} + \textbf{Rotation Matrices} \begin{bmatrix} x_1 \\ y_1 \\ z_1 \end{bmatrix}$$

$$\textbf{Rotation Matrices} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & -\sin\alpha \\ 0 & \sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} \cos\beta & 0 & \sin\beta \\ 0 & 1 & 0 \\ -\sin\beta & 0 & \cos\beta \end{bmatrix} \begin{bmatrix} \cos\gamma & -\sin\gamma & 0 \\ \sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (3)$$

where the angle α resembles rotation about the x-axis, the angle β resembles rotation about the y-axis, and the angle γ resembles rotation about the z-axis

3. Predefined Topological Relations

Besides the topological/geometry representation of building elements, AutoDesk Revit BIM Model contains predefined relationships between certain types of elements. For instance, in the door and window type properties, the property: wall closure identifies the hosting element whether it is a wall or a skylight in a roof. Hence, the instance's properties define its hosting predecessor element (the element's topological relations).

E. Automatic Deduction of Topological Relationships

In order to automatically generate the EGDM, BIM-based algorithm is proposed to deduce the topological relationships among building elements by means of the creation of a bounding box (generated from element's retrieved min and max points) surrounding the elements, and, hence, deducing the predecessor/dependent elements, as demonstrated in Fig. 9. The algorithm extracts the four major types of topological information: connectivity, containment, separation, and intersection as defined by [2].

Reference [2] proposed an algorithm that extracts the topological relationships from 3D geometric data indicated in a CAD model, which is not efficient in terms of computation and data storage. Furthermore, unlike topology-driven models, geometry-driven models need geometric modifications for further analysis [3]. Using geometric/topological representations in AutoDesk Revit, the proposed BIM-based algorithm enhances deduction in three ways. First, AutoDesk Revit BIM Model may be used to directly extract the topological primitives and their geometric information instead of obtaining them from lines and points in a CAD environment. Second, the AutoDesk Revit BIM Model building elements representations cover a wider range of elements when compared to conventional CAD modeling. Third, AutoDesk Revit BIM Model comprises predefined relationships between certain types of elements, eliminating the need for deducing their relationships. Hence, reducing computation time and complexity.

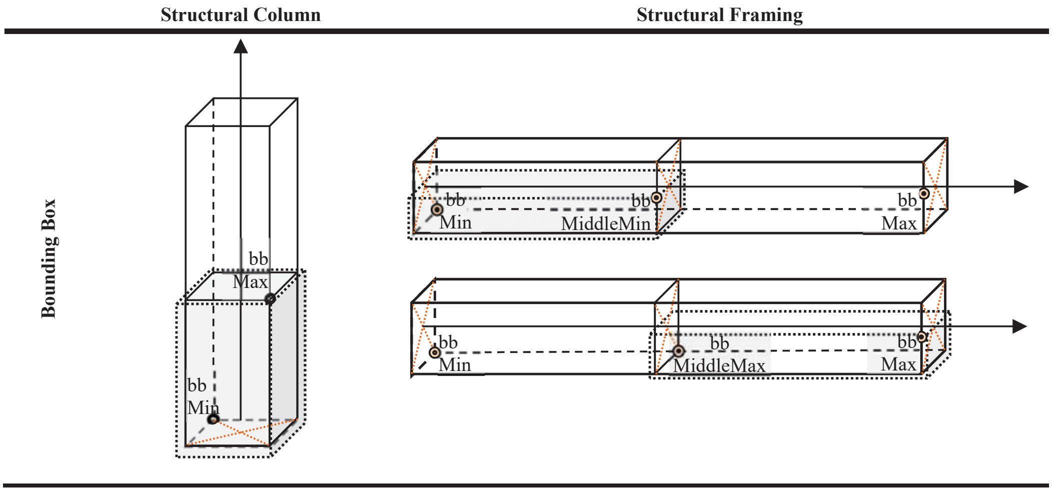


Fig. 9 Structural Column and Structural Framing Bounding Boxes

The following describes how the topological relationships are identified using AutoDesk Revit competences.

Connectivity: For each building element, the algorithm determines its topological relationships by creating a bounding box surrounding the element and obtain all predecessor building elements that are in contact with it.

Containment: This type of topological information arises only in one case where building elements that are hosted by others, for example walls hosting doors and windows. In this case, a bounding box is created surrounding the selected element and all the overlapped building elements are identified.

Separation: When two building elements are separate from each other, there is no topological primitive in common. Therefore, the conditions for separation are the converse of those for containment. To identify the "Separation" relationship among building elements, the algorithm creates a bounding box surrounding the selected element and obtains all building elements that do not intersect or overlap with it.

Intersection: The intersection relationship identifies if two different building elements intersect one another. Intersection has various applications in structural analysis, site layout planning and constructability analysis. To determine the condition of intersection between the given building elements, the algorithm creates a bounding box surrounding the selected element and checks all building elements that intersect with it.

Examples to demonstrate the deduction of the topological relationships are presented in Fig. 10 andFig. 11.

F. Computer Implementation

BIM is capable of recognizing building elements in its fixed asset hierarchy (Family - Type - Instance) while being user-friendly for visualizing the alternatives. AutoDesk Revit customization capabilities have been significantly extended over the past few years. AutoDesk Revit Application Programming Interface (API) allows users to program with any .NET compliant language such as VB .NET and C# .NET.

.NET Framework is a programming infrastructure developed by Microsoft that runs primarily on Microsoft Windows. It includes a large class library known as Framework Class Library and provides language interoperability across several programming languages. It includes a large library of coded solutions to prevent common programming problems and a virtual machine that manages the execution of programs written specifically for the framework. The application main development language is C#, based on .Net framework 4.0 platform and has been written using Microsoft Visual Studio Integrated Development Environment (MS VS IDE). C# is a multi-paradigm programming language encompassing strong typing, imperative, declarative, functional, generic, object-oriented (class-based), and component-oriented programming disciplines. Through its use of Extensible Markup Language (XML) and Simple Object Access Protocol (SOAP), it allows access to a programming object or method without requiring the programmer to write additional code for each step [21].

The application uses AutoDesk Revit SDK and AutoDesk Revit APIs to communicate with AutoDesk Revit Software. AutoDesk Revit Software Development Kit (SDK) is a programming package that enables programmers to develop applications.

VI. CONCLUSIONS

This research develops a semantically enhanced, 3D topological data model, the EGDM, to represent the topological relationships among building elements. The proposed model exploits BIM capabilities for geometric/topological representation, thus simplifying the abstraction of the topological relationships among building elements using the vertex-edge structure of the graph. The semantic information is added as weights to vertices and edges and is termed SDT.

The elements of the proposed EGDM make it an elaborated intelligent model to represent topological relationships that will be able to handle wide ranges of queries efficiently. Having a graph data structure, complex topological queries can be implemented through advanced graph algorithms. Moreover, SDT makes the EGDM a knowledge-embedded model, which would be able to run rule-based queries and constraints.

The EGDM presented in this paper contributes to the advancement of research in the area of 3D topological models for A/E/C applications and also overcomes several limitations of the existing models in the following ways: first, it explicitly represents the building elements (structural and nonstructural) of buildings using a graph data structure; second, because the proposed model is not limited to any specific geometric representation of building elements, a wide range of building elements can be modeled. Third, using AutoDesk Revit APIs as a data-exchange platform enables the EGDM to exploit the predefined topological relationships in a BIM Model to significantly reduce the deduction time. Fourth, previous graph data models, such as those developed by [2]-[4], are limited to adjacency and connectivity for the sake of specific purpose of finding shortest path among spaces in a building, whereas the EGDM covers all four major spatial relationships for all A/E/C applications. Fifth, the proposed EGDM is enriched with the semantic information obtained from the BIM Model which

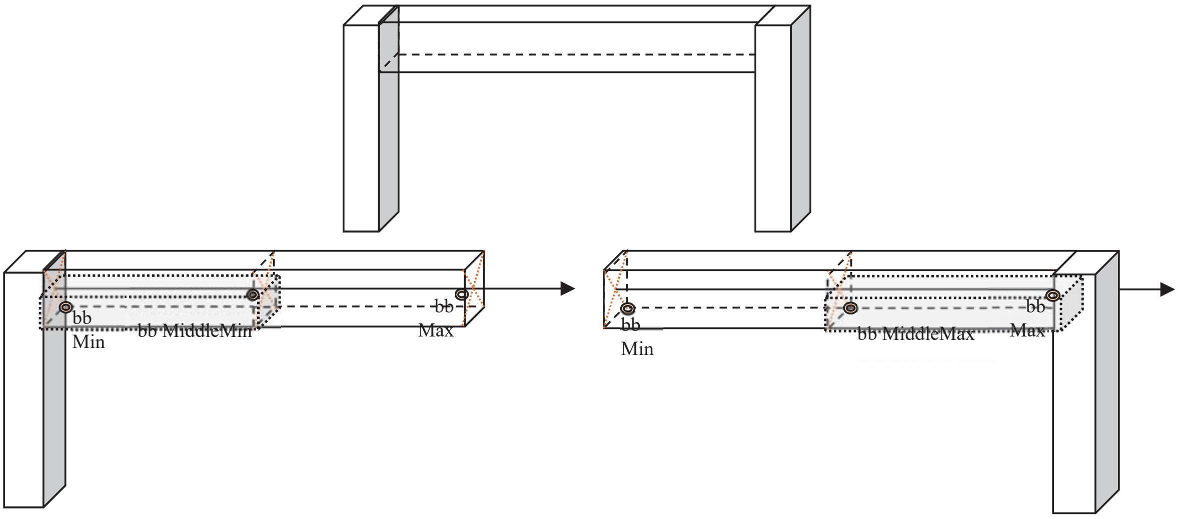


Fig. 10 Structural Framing Dependency – Single Frame

enables the handling of complex semantic-based queries for different project stakeholders. Sixth, and finally, network-based analyses can be performed to maintain computational efficiency while avoiding storage of massive geometric data of complex buildings.

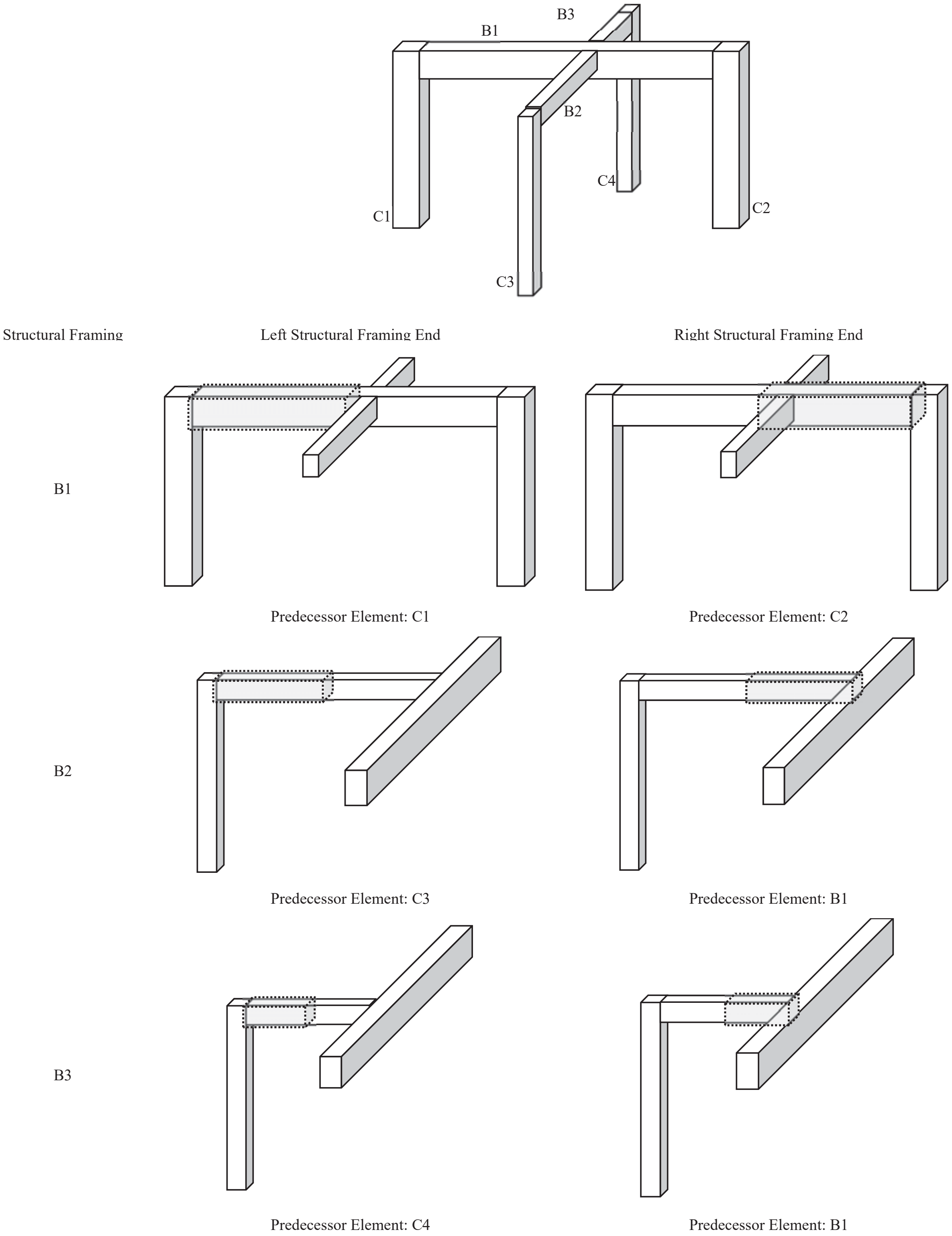


Fig. 11 Structural Framing Dependency – 2 Intersecting Frames

The EGDM, serving as the first part of a research, is, then, utilized and graph search algorithms, such as DFS and topological sortings, are performed to generate all possible construction sequences. The sequences are, then, compared against production and construction rules to generate an optimized construction sequence and a better cost and time trade-off. And, finally, recommend the Optimized Elemental Construction Method, Schedule and Resources, and, hence, generate 4D and 5D BIM models.

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