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PARAMETRIC GEOMETRIC MODELING IN CONSTRUCTION PLANNING USING INDUSTRY FOUNDATION CLASSES

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Abstract. *One of the most promising and recent advances in computer-based planning is the transition from classical geometric modeling to building information modeling (BIM). Building information models support the representation, storage, and exchange of various information relevant to construction planning. This information can be used for describing, e.g., geometric/physical properties or costs of a building, for creating construction schedules, or for representing other characteristics of construction projects. Based on this information, plans and specifications as well as reports and presentations of a planned building can be created automatically. A fundamental principle of BIM is object parameterization, which allows specifying geometrical, numerical, algebraic and associative dependencies between objects contained in a building information model. In this paper, existing challenges of parametric modeling using the Industry Foundation Classes (IFC) as a federated model for integrated planning are shown, and open research questions are discussed.*

1 INTRODUCTION

A characteristic feature of building information modeling is the creation of parameterized dependencies between individual objects. Parameterized dependencies allow changes in the building information model to be done automatically and simultaneously. Since, in practice, the planning process is iterative and interactive, parameterized geometric modeling is an invaluable tool to quickly and correctly change construction plans or schedules.

State-of-the-art BIM software, such as Autodesk Revit 2016 [1] and Nemetschek Allplan 2015 [2], provides a large number of default parametric dependencies, such as relationships between the coordinate axes of a building and the position of components or relationships between roof shapes and wall heights. The use of this default parameterization enables easy modifications of BIM models. Furthermore, it becomes possible to modify the description of the model (or of the construction plans or schedules, respectively). BIM software can also be used to create individual relationships between objects of a model and to develop individual data structures. However, for the following reasons, using BIM software requires expert knowledge and is thus limited to IT specialists ("BIM managers") or to a few BIM enthusiasts:

- High psychological barrier as compared to traditional (and well-known) planning principles

- Implications of object orientation of the software products

- Lack of understanding of parametric modeling

This paper addresses the use of parametric modeling in the context of building information modeling. First, the definition of parameterization is introduced in methodological terms, followed by the description of parameterization types for geometric objects and models. Next, an overview of the parameterization types used in the area of construction planning is given. Then, the type of associative geometric parameterization in conjunction with BIM is analyzed, using an integrated planning scenario as an illustrative example. The paper concludes with a summary and a discussion.

2 METHODOLOGY

Essentially, geometric modeling is the representation of objects with respect to their shapes, dimensions, and orientations. According to Golovanov (2011), computer-aided geometric modeling "teaches the methods to create numerical models using either real geometry or the object to be depicted, as well as the methods of how to deal with such models. The geometric model contains a form description of the object to be depicted and the description of the connections between the model elements" [3].

The foundation of BIM is a 3-dimensional geometric model. However, the geometric model is not only based on some geometric primitives such as cones or cylinders; it is rather based on object-oriented elements that describe the object under construction or elements of the object, such as beams, supports, or ceiling panels. Nevertheless, geometric properties of an object, or of an object's element, such as shapes, dimensions and orientations, are described similar to the properties of the geometric primitives.

The methodology shown in this paper supports an easy understanding of the major parametric dependencies of geometric modeling. Thus, planners are enabled to easily define simple parametric dependencies, even if only traditional CAD software instead of state-of-the-

art BIM software is used. In the following subsections, a concise literature review on parameterization is provided, followed by an overview of the parameterization types used in the area of construction planning.

2.1 A concise literature review on parameterization

Parameterization is a mathematical term that includes

i. removal of object properties,

ii. description of object properties with parameters, and

iii. determination of the relationships between these parameters.

Borisov, et al. (1998) define parameterization as follows [4]: „Parameterization is a concept that includes all methods of construction planning. One important characteristic of the modern parametric design planning concept is, in particular, the ability to create geometric models with relationships and rules which can be changed and complemented at every stage of its development. The rules are defined as conditions for basic operations". Thus, parameterization can be considered as a methodology in computer-aided construction planning, which allows, at an early stage, a conceptual design of an object to be created with defined dependencies that can, in a later stage, be adapted to changes and developments of the project. Borisov et al. (1998) have also defined terms describing the technology and the methods for creating parameterization models.

Yermilov et al. (2004) have considered the parameterization of geometric kinematic models in the design process [3]; the authors have described the advantages and foundations of parametric modeling. Koropushkin (2005) has classified parameterized models and proposed calculation algorithms for these models [6]. Erochin (2013) has studied the parameterization of geometric models in aircraft design, particularly models that allow the parameterization of shapes and their orientation in space. Also considering aircraft design, a methodology for the development of parametric models is proposed in [7]. Classifying the tasks of parameterized geometry in geometric constructions, Salkov (2014) has proposed a definition for the term „parameter", demonstrating that parameterized geometry is founded on the method of iterative design [8]. Butorov and Eresko (2012) have presented an overview of methods for parameterized modeling, including advantages and disadvantages. Widely-used CAD systems that use parameterization have been reviewed and practical applications of computer-aided parameterized modeling have been considered in [9]. As an example of parameterization of geometric models in disciplines apart from engineering, Serjodkin et al. (2014) have investigated models and the methodology of parameterization for computer-aided design approaches in the shoe industry [10].

In summary, parameterization is widely applied in the design process and in several areas within computer-aided design (CAD), computer-aided manufacturing (CAM), and computer-aided engineering (CAE) [11,12].

2.3 Parameterization types for geometric objects and models

This subsection briefly summarizes the of parameterization for geometric objects and models.

Geometric parameterization: Geometric parameterization is the creation of topological relationships, i.e. the generation of relationships between basic geometric elements such as lines, circles, etc. Examples are the parallelism of edges, the coverage of circle centers, or strict horizontal or vertical orientation of lines. The characteristics of geometric parameterization are

not described by numerical parameters, but rather by geometric terms, such as position, alignment, direction, etc.

Numerical parameterization: Numerical parameterization enables the determination of numerical characteristics for geometric objects and their geometric shapes, for example the length of a geometric section, angular dimensions, or distances between points. The characteristics are described through parameters, which can be modified depending on the modeling task. The parameters also influence the geometric shape and the position of an object. In this sense, this type of parameterization is mainly used for describing the geometric dimensions of an object.

Algebraic parameterization: Algebraic parameterization is the creation of mathematical expressions to describe the interrelation between numerical parameters of a geometric object. Examples are the parity of geometric section lengths, the proportionality between height and width of a geometric object, and the limits of object volumes. This type of parameterization allows not only the use of geometric parameters in the algebraic expressions; it also allows considering non-geometric parameters, e.g., time, cost or physical parameters.

Associative parameterization: Associativity implies information linkage between the geometric model and other model types, objects, or processes. Examples are the detailing of model representations in different scales, the reproduction of the geometric model properties in text form, or the mapping of documents into a database. If changes to an object occur, all associated objects will change accordingly.

3   PARAMETERIZATION IN CONSTRUCTION PLANNING

Since state-of-the-art BIM software provides parametrization, the concept of parameterization is widely used in construction planning. In this section, an overview of the parameterization types used in the area of construction planning is given. Then, the types of associative geometric parameterization in conjunction with BIM are analyzed, using the IFC as a federated model within an integrated planning scenario that serves as an illustrative example.

3.1 Overview of parameterization in construction planning

Automation of standard construction procedures: Standard procedures for the geometric modeling of objects, having several dimensions, can advantageously be automated using parameterized relationships between individual objects. The overall set of relationships has to be created for the automatic recalculation of object geometries. In this way, a change in any parameter will be automatically applied to the entire model. For example, the construction of dimension lines and anchoring them to the object contour must be executed only once.

Working with variables: Using variables to parameterize the geometric shape of objects enables a simple and targeted way of model modification. Thus, the planner can quickly design and review alternative design solutions.

Calculating optimum solutions: The possibility of describing a model through parameters allows not only creating alternative options, but also computing optimum solutions, such as dimensions, building volumes, or areas.

Execution of changes: The process of construction planning in engineering practice is a distributed-cooperative process comprising of several iterations and alterations. The geometric parameterization and associative relationships allow developing construction plans or schedules in a way that any alteration can be applied immediately and provided automatically to all

parties participating in the project. At the same time, an automatic representation of all changes is possible.

Parallel planning: Parameterized geometric modeling is the foundation of cooperative work, facilitating architectural and engineering design processes, structural calculations, building installations, and construction works that can be brought together. Conceptual planning on the basis of parameterized geometric modeling enables all processes, even those associated with uncertain or undefined parameters, to be executed faster as compared to conventional approaches.

Parameterization as a programming element of properties: The process of creating and storing analytical relationships between objects is similar to the paradigm of object-oriented programming. The addition of logical and associative relationships supports the generation of project reports, bills of materials, drawings, and other project-related documents.

3.2 Parameterized modeling in the context of BIM

Summarizing the previous sections, it can be concluded that parametric modeling is an important methodology for creating building information models. Considering BIM, it should be emphasized that one of the main objectives of BIM is integrated digital construction planning, which requires the use of a standardized digital data format. This data format serves either as a federated building information model, or it provides a standardized exchange format for all participating planners. However, it is questionable if parametric modeling can be reliably supported through software applications based on a standardized data format. In the following paragraphs, this question is investigated by means of an example using the IFC as a federated model simulating a cooperative construction planning process. In the example, the cooperative construction planning process is simulated as a six-step process including different model imports and model exports, different state-of-the-art software applications (Autodesk Revit 2016 and Nemetschek Allplan 2015), and different model viewers (IFC TOOLS PROJECT Viewer [13] and Solibri Model Viewer v9 [14]).

In the first step, an initial model is created, representing the first story of a building that consists of four walls, two windows, a ceiling, and a door. Using Autodesk Revit 2016, the heights of all walls are parameterized as the distance between level 1 and level 2 (Figure 1). In other words, if the height of the first story changes, the height of all connected walls changes accordingly. Figure 1 illustrates the example, including the parameterized constraints "Base Constraint", defining the wall's base being parametrically connected to level 1, and "Top Constraint", defining the wall's top being parametrically connected to level 2.

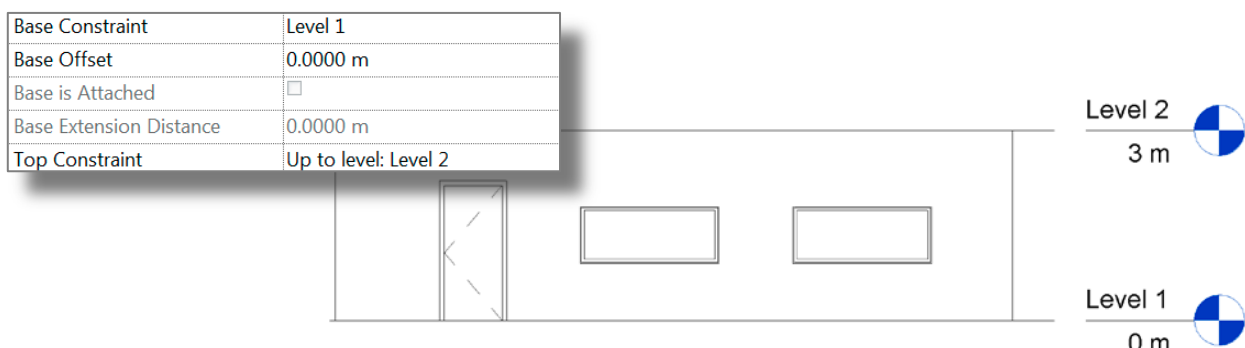| Base Constraint | Level 1 |
Base Offset	0.0000 m
Base is Attached	☐
Base Extension Distance	0.0000 m
Top Constraint	Up to level: Level 2

Figure 1: Autodesk Revit 2016 original file: The wall is parametrically connected to level 1 (bottom) and to level 2 (top)

In the second step, the Autodesk Revit 2016 model is exported as an IFC 2X3 file. Then, in the third step, it is reimported into the same (Autodesk Revit 2016) application. As can be seen

from Figure 2, this fairly simple task results in an inconsistent model. Specifically, the previously defined "Top Constraint" is missing, i.e. it is changed from "Up to level: Level 2" to "Unconnected".
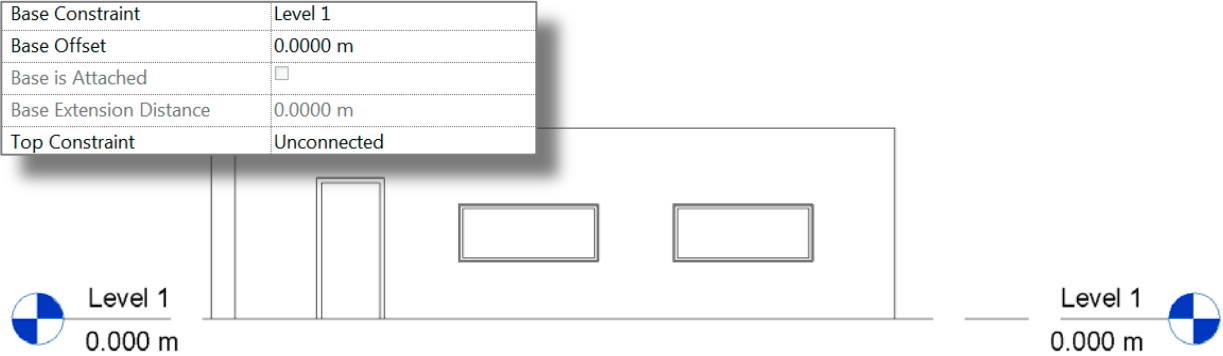
| Base Constraint	Level 1
Base Offset	0.0000 m
Base is Attached	☐
Base Extension Distance	0.0000 m
Top Constraint	Unconnected

Figure 2: Result after exporting and reimporting the Autodesk Revit 2016 model as IFC 2X3 file: The wall is no longer parametrically connected to level 2 (top), and level 2 is missing

In the fourth step, the exported IFC file is evaluated. The constraints of interest is exported as user-defined IFC Property Sets, where the "Top Constraint", as shown in Figure 3, is set to "Level: Level 2". For this reason, the reimport should have been performed properly. However, this is not the case here (which is an assumption, because the information expressed by these Property Sets is not part of the IFC standard).

Object/Attribute	Value	Property Set	Type
Base Constraint	Level: Level 1	Constraints	IfcPropertySingleValue
Base Extension Distance	0.0	Constraints	IfcPropertySingleValue
Base Offset	0.0	Constraints	IfcPropertySingleValue
Base is Attached	false	Constraints	IfcPropertySingleValue
Location Line	Core Face: Exterior	Constraints	IfcPropertySingleValue
Related to Mass	false	Constraints	IfcPropertySingleValue
Room Bounding	true	Constraints	IfcPropertySingleValue
Top Constraint	Level: Level 2	Constraints	IfcPropertySingleValue

Figure 3: Connected Property Set of the walls (excerpt): IFC 2X3 export from Autodesk Revit 2016
(screenshot taken using the IFC TOOLS PROJECT Viewer [13])

The further steps describe a more realistic scenario, in which the previously exported IFC model, created by planner A, is provided to another participating planner B (step five). Planner B performs changes to the model using a different software product, Nemetschek Allplan 2015, in which the IFC model is imported. In the Nemetschek Allplan 2015 model, planner B shortens the wall containing the windows and the door by 40 cm. As a result, after exporting the modified Nemetschek Allplan 2015 model as IFC 2X3 file, the geometric model displays correctly (as compared with the Nemetschek Allplan 2015 model resulting from step five) as shown in Figure 4.
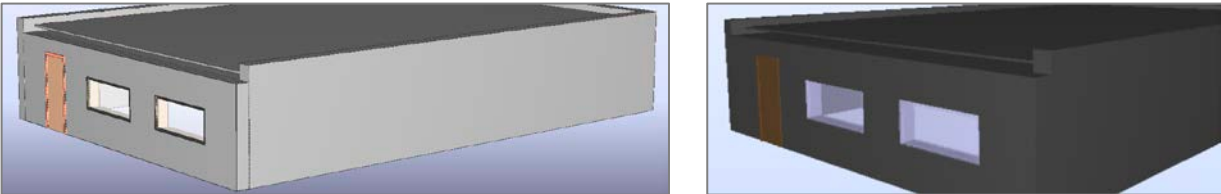
(a) IFC TOOLS PROJECT Viewer   (b) Solibri Model Viewer v9
Figure 4: Screenshots visualizing the modified Nemetschek Allplan 2015 model

Evaluating the IFC file exported from the Nemetschek Allplan 2015 model, it can be seen that all Property Sets created in the Autodesk Revit 2016 model are missing. Instead of those Property Sets, new Property Sets (obviously belonging to Nemetschek Allplan 2015) have been inserted. Figure 5 shows the Property Sets connected to the modified wall. Interestingly, an attribute "Top Constraint" with a "Level: Level 2" value still exists. Furthermore, an attribute "Top Offset" is set to "0.0" and an attribute "Unconnected Height" is set to "3.0", which represents the total height of the modified wall. This height, however, should be reduced by 40 cm, or a corresponding "Top Offset" should be set. Again, it must be noted that this is only an assumption, because the information expressed by these Property Sets is not part of the IFC standard.

Object/Attribute	Value	Property Set	Type
Top Constraint	Level: Level 2	Allplan Attributes	IfcPropertySingleValue
Top Extension Distance	0.0	Allplan Attributes	IfcPropertySingleValue
Top Offset	0.0	Allplan Attributes	IfcPropertySingleValue
Top is Attached	false	Allplan Attributes	IfcPropertySingleValue
Type	Basic Wall: Generic – 375mm	Allplan Attributes	IfcPropertySingleValue
Type Id	Basic Wall: Generic – 375mm	Allplan Attributes	IfcPropertySingleValue
Type Name	Generic – 375mm	Allplan Attributes	IfcPropertySingleValue
Unconnected Height	3.0	Allplan Attributes	IfcPropertySingleValue

Figure 5: Connected Property Sets of the modified wall (excerpt) – IFC 2X3 export from Nemetschek Allplan 2015
(screenshot taken using the IFC TOOLS PROJECT Viewer [13])

In step six, the model is converted back to planner A's software, i.e. into an Autodesk Revit 2016 model. As can be seen from Figure 6, the geometric model is incorrect: The heights of three out of four walls are changed. Precisely, the heights are reduced by 208.6 cm.
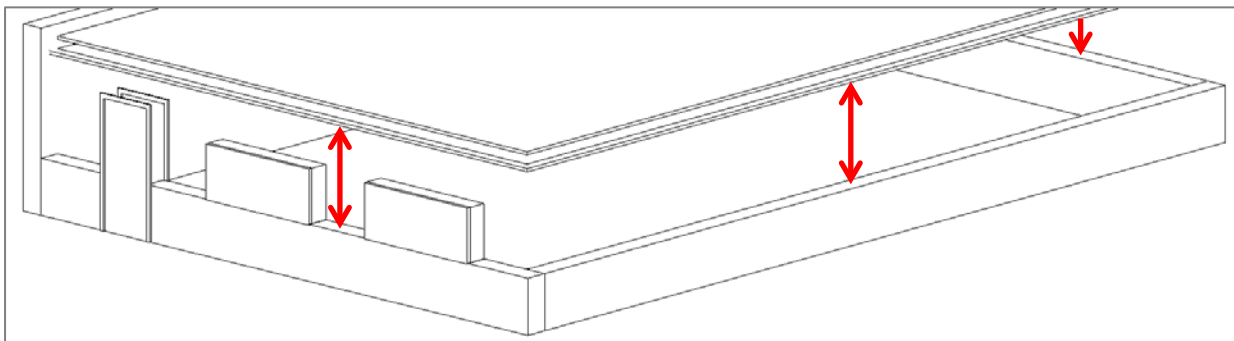

Figure 6: Result after importing the modified IFC file using Nemetschek Allplan 2015 into Autodesk Revit 2016

4 SUMMARY AND DISCUSSION

As demonstrated in this paper, geometric parameterization is a powerful modeling methodology in the context of building information modeling. BIM supports the representation, the storage, and the exchange of various information relevant to construction planning. This information can be used for describing, e.g., geometric/physical properties or costs of a building, for creating construction schedules, or for representing other characteristics of construction projects. Based on this information, plans and specifications as well as reports and presentations of a planned building can be created automatically. In addition, the use of BIM allows for a better way of cooperation within the construction planning process. However, cooperation requires a common digital data format for model exchange. The given example, which illustrates an integrated planning scenario using the IFC standard as federated model, has shown that parametric modeling may lead to inconsistent models if different software applications are used. In conclusion, additional research efforts are required to further

investigate the parameterized geometric modeling in conjunction with building information modeling.

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