A New Automated Quantity Takeoff Method for BIM-Based Bridge Designs

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Abstract
In recent years, there has been a mounting interest in the architecture, engineering, construction and facility management (AEC/FM) community to adopt Industry Foundation Classes (IFC) models in their engineering and management processes. While the abundancy of physical and functional information offered by an IFC model is evident, the use of IFC model for quantity takeoff purpose yet did not achieve full automation. The main challenge in describing quantities with semantic properties (e.g., overall height, overall width) in an IFC model for automated quantity takeoff is that it requires manual quantity input during the authoring of an IFC model and thereby brings down the level of automation in the use of IFC models overall in quantity takeoff tasks. To address the challenge, in this paper, a new method is proposed for automated quantity takeoff from an IFC-based bridge model. In the proposed method, geometric shape representation data (e.g., Cartesian point) in an IFC model are analyzed for developing automated quantity takeoff algorithms. The automated quantity takeoff algorithms analyze the Cartesian points that describe the geometry of piers and deck of the bridge directly and takes off the measures of length, width, height (i.e., thickness), cross sectional area and volume for each bridge component. To test the proposed method, a preliminary experiment was conducted where a simple bridge model (i.e., one bridge deck and four piers) was created in MicroStation V6 and exported into an IFC model for testing. The proposed automated quantity takeoff method was implemented in a java program and applied to a testing IFC-based bridge model. Quantity takeoff algorithms generated by the method were successfully tested on the testing bridge model and three other randomly retrieved bridge models, yielding quantity measures for their deck and piers with only minor differences from manual extraction results due to rounding errors.

Keywords: Construction automation, Quantity takeoff, Cost estimation, Building information modeling, Industry foundation classes

1 Introduction
Cost estimation is an essential process in a construction project for multiple purposes, such as bid preparation and project management. It is the process of estimating the costs required to perform all the work within the scope of a construction project. Accurate cost estimation is a time consuming activity, especially for construction contractors. Though there are a noteworthy number of construction cost estimation tools, human estimators still have to invest a large amount of effort in the cost estimation task. Currently, Industry foundation classes (IFC) provides an open and neutral information exchange standard covering architectural, structural, Heating Ventilation and Air Conditioning (HVAC), and electrical subdomains among others in the construction domain. IFC standard was developed by buildingSMART [formerly International Alliance for Interoperability (IAI)] to provide a foundation for the exchange and

sharing of information between software applications in the construction domain (buildingSMART 2016). It helps define a shared building project model – an IFC model. An IFC model defines physical building objects, their attributes and inter-relationships mainly in the form of an interconnected hierarchy of entities and attributes. The IFC hierarchy represents project information such as building components, the geometric and material properties of building components, project costs, schedules, and organizations. As of today, buildingSMART has published several versions of the IFC schema and it is continuously updating the IFC schema to enable the representation of more building and construction information (buildingSMART 2016). The abundancy of physical and functional information offered by an IFC model enable it to be used in the automation of cost estimation. For example, Tanyer & Aouad (2005) developed a 4D planning tool that leveraged the design results of IFC files for cost estimation. Yabuki & Shitani (2005) developed a 4D model-based earthwork management system that leverages IFC2X standard to represent a process model, for supporting scheduling and cost estimation tasks. However, in these research works, it still requires manual quantity input during the authoring of an IFC model and/or extra efforts in quantity computation. It thereby brings down the level of automation in the use of IFC model overall in quantity takeoff tasks. To address the challenge, in this paper, a new method is proposed for automated quantity takeoff from an IFC-based bridge model, in which geometric shape representation data (e.g., Cartesian point) in an IFC model are directly used for quantity takeoff purpose. The method reduces the amount of manual effort needed for quantity input into IFC-based bridge models, therefore pushes the automation of IFC-based bridge cost estimation one step further.

2 Background

Industry foundation classes (IFC) is a comprehensive schema of the building and construction industry data. As a major data standard for building information modeling (BIM), it provides a foundation for the collaboration of different stakeholders on a building and construction project. However, the use of IFC models in cost estimation is still problematic: on one hand, there are more than 600 entities defined in the IFC schema and not all of them are needed to support cost estimation (Xu et al 2013); on the other hand, the majority of information in an IFC model are data from the resources layer, including geometrical data, orientation data, and contextual data (e.g., unit of measure) (Nour 2009). These majority of information use a limited set of IFC entities to describe product models for a multitude types of projects such as buildings and bridges. Hence, it is important to analyze the usage of IFC entities in different types of projects and select the suitable ones to use in a sector-specific automated cost estimation system, which is still largely lacking.

Quantity takeoff is probably the most time-consuming and inefficient part of construction cost estimation without automation (Alder 2006). It is central, however, in defining the amount of resources needed for the later steps of cost estimation. The traditional manual quantity takeoff process is time-consuming and error prone. For example, it is common to observe missing elements or double counting in a manual quantity takeoff. New software can help reduce the manual efforts needed for quantity takeoff substantially. The use of a standard data schema such as the IFC schema can facilitate the interoperability among different software tools. The nature of the IFC schema as a standard specification for sharing building and construction industry data throughout the life cycle of a project encourages the researchers globally to develop intelligent solutions based on IFC for future automated applications. Accessing the information in IFC models computationally is a premise for such applications. There have been a lot of efforts that focused on automating the information extraction from IFC models. These efforts leveraged information both from the IFC models (e.g., Faraj et al 2000, Borrmann & Rank 2009) and from the IFC schema (e.g., Zhang & El-Gohary 2015; Pauwels & Terkaj 2016). Both types of information can support the implementation and usage of automated IFC-based applications. Based on the IFC schema, the architecture of an IFC model boils down to poly loops and Cartesian points when representing geometries of building objects. Each poly loop consists of a group of Cartesian points, and each Cartesian point describes a point of the model geometry in three dimensional space. As the basis for geometric representation, IfcCartesianPoints take a big portion in most IFC models. For example, Nour (2009) shows that the percentages of IfcCartesianPoints in their two compared IFC models reached 25% and 32% of all elements in the two IFC models, respectively. These fundamental geometric elements may be leveraged to facilitate automated quantity takeoff.

Automated information extraction from IFC models for the sake of quantity takeoff is the first step to achieve automated cost estimation using IFC model, and there are a few research work pursuing such automated cost estimation. For example, Choi et al (2015) proposed a quantity takeoff system which could automatically extract building frame elements' quantities from IFC models. Fu et al (2004) presented a system for simulating building lifecycle costs of building construction and maintenance that can automatically retrieve dimensional information of building components and display them in a graphical IFC viewer. However, in these research works, attribute-driven geometric representation in IFC models are used for quantity takeoff. The authoring of quantity information, thus, still requires manual efforts, with a lack of full leverage of geometric representation inherent in IFC models. Therefore, there is a research gap in leveraging Cartesian points level of information for quantity takeoff, which can lend to an automated quantity takeoff method suitable for a general scope of building and construction projects. To address this research gap, the authors propose a new method for automated bridge model quantity takeoff leveraging Cartesian points from an IFC-based bridge model.

3 Proposed Method

A four-step method is proposed here (Figure 1): (1) define the type of object to take off quantity for; (2) study the representation of the defined type of object in IFC; (3) develop the quantity takeoff algorithm for each selected type of object; and (4) test the quantity takeoff algorithm on unseen data.

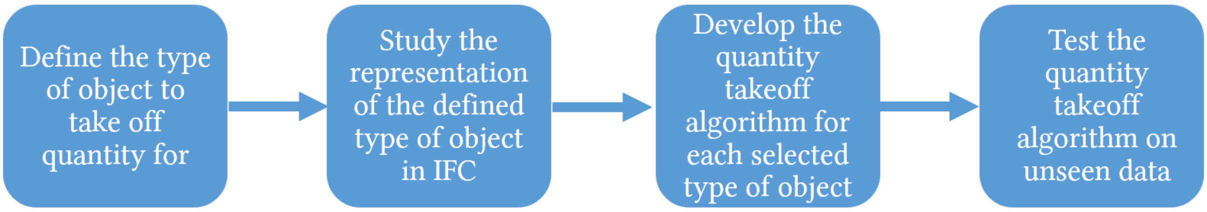

Figure 1 Proposed method

The proposed method focuses on developing algorithms for the quantity takeoff task from a bridge design model. The main input of the proposed method is an IFC bridge model (i.e., the development model). The output would be quantity takeoff algorithms for bridge components. To better illustrate the proposed method, the deck and piers of a bridge model are used as examples. The proposed method analyzes the Cartesian points that describe the geometry of piers and deck of the bridge directly and takes off the measures of length, width, height (i.e., thickness), cross sectional area and volume for each bridge component.

3.1 Step 1 - Define the type of object to take off quantity for

This step identifies and defines the type of bridge object to take off quantity for. Bridges are geometrically multifaceted civil engineering structures. The components of a typical bridge need to be represented by different geometric entities and curved surfaces, which benefits from the three dimensional model representations using IFC. To better serve the representation of bridge components, IFC-Bridge was added to the IFC schema (Lee & Kim 2011). However, depending on the workflow of authoring a bridge model, the entities and attributes from IFC-Bridge are not necessarily used in the representation of bridge components. For example, Figure 2 shows the development model composed of one deck and four piers. This model was created using MicroStation V6 (Bentley 2016a) where basic bridge elements (i.e., deck, piers) were created in MicroStation V6 and converted into IFC format in AECOsim building designer (Bentley 2016b). As a result the development model did not use IFC-Bridge entities in the whole model representation at all. Therefore, to ensure the usability of quantity takeoff algorithms to be developed in later steps, this first step in the proposed method identifies and defines the type of a bridge object corresponding to a specific model authoring workflow. The type of a bridge object is identified and defined based on its particular shape.

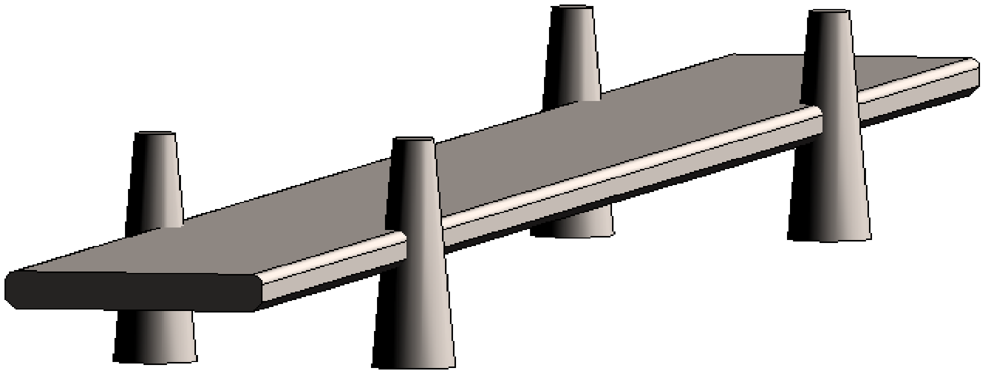

Figure 2 A simple bridge model

3.2 Step 2 - Study the representation of the defined type of object in IFC

This step studies the interrelationships between the IFC entities and bridge elements covering all areas of the defined type of object. Although IFC4 (buildingSMART 2016) was already released, IFC2X3 is still the most widely used IFC schema in practice, therefore the proposed method focused on the IFC models using IFC2X3. IFC2X3 is composed of 635 entities among which 53 entities belong to the subset of IfcElement. These 53 entities are basic entities to represent building elements. The study of representation in this step follows a selected IFC model authoring workflow. The MicroStation-based workflow described in Section 3.1 was used in this illustrative example. Example IFC entities studied include IfcStyledItem, IfcPolyLoop, and IfcCartesianpoint, etc. In the development model used, the geometry of the deck was represented by a solid shape slab with fillet edges at the top and bottom. The geometry of a pier was represented by a solid shape cone frustum with different top and bottom radius. It was found that the geometries of bridge deck and piers were both represented using IfcStyledItem in the IFC model.

3.3 Step 3 - Develop the quantity takeoff algorithm for each selected type of object

This step makes use of the knowledge gained from Step 2 and develops a quantity takeoff algorithm for each selected type of object. The algorithms are based on analyzing the basic geometric representation entities such as IfcPolyLoop and IfcCartesianpoint for the selected objects. The algorithms also leverage the representation structure (i.e., IFC entities and their relationships) for each object in IFC. All quantities will be taken off using Cartesian points. Equation (1) is a general formula for calculating the distance between two Cartesian points (*A* and *B*) in three dimensional space. *X1*, *Y1*, and *Z1* represent the Cartesian coordinates of point *A*, and *X2*, *Y2*, and *Z2* represent the Cartesian coordinates of point *B*. Equation (1) forms the basis of all length calculation in the Cartesian point-based quantity takeoff algorithms.

$$Distance\ AB = \sqrt{(X2 - X1)^2 + (Y2 - Y1)^2 + (Z2 - Z1)^2} \quad (1)$$

To simplify the geometric calculations, an assumption was adopted that the pose of a bridge is vertical (or with negligible tilts). For the solid slab-shaped deck with fillet edges in the development model, the main geometry was represented by an IFCStyledItem. The IFCStyledItem instance was further represented by a total of 16 poly loops and 34 Cartesian points. Among these 34 Cartesian points, the ones with greatest positive Z value are the top edge points. As shown in Figure 3, there are equal number of edge points on each side of the deck (one of them is highlighted). These edge points were visualized by plotting in the 3D

Point Plotter platform (Hotmath 2016). Using two edge points from both ends of the slab and Equation (1), the length of the deck can be calculated. Consider a top edge point and its symmetric point vertically, using Equation (1) the height/thickness of the deck can be calculated (Figures 3 & 4). As the deck is chamfered on the sides, the Cartesian point with greatest positive Y value and the Cartesian point with the least negative Y value were used in Equation (1) to find the width of the deck (Figures 5 & 6). Next, the cross sectional area of the deck can be found by dividing the cross sectional surface into horizontal stripes, calculating the area for each stripe, and finding the summation. In the bridge deck being analyzed, four edge points on each side were used (Figure 7). The cross sectional area were divided into three horizontal stripes. Using the eight edge points (i.e., four pairs) on both sides, Equation (1) can be used to find the distance between each pair of them. Using Z coordinates differences between the vertically adjacent edge points, the heights for each stripe can be found. Then Equation (2) can be used to find the cross-sectional area of each stripe. In Equation (2) for calculating the area (*A*) of a stripe, *a* represents the length of the top side, *b* represents the length of the bottom side, and *h* represents the height. The summation of the areas of all stripes is the area of the cross section. The volume of the deck can be found by simply multiplying its length and its cross sectional area.

$$Stripe\ Area\ A = (a + b) * h/2 \quad (2)$$

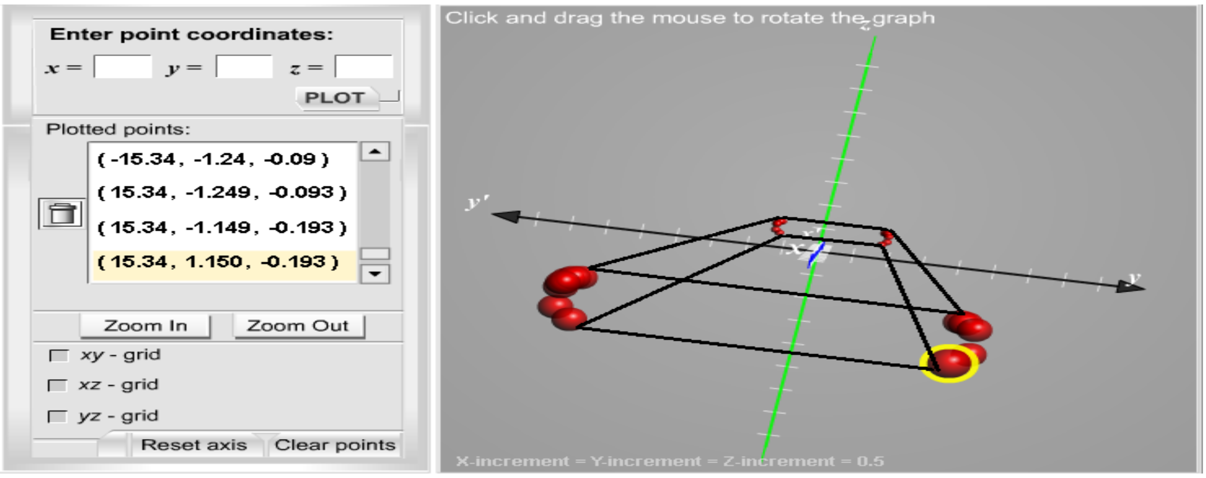

Figure 3 Edge points of the deck with the bottom right one highlighted

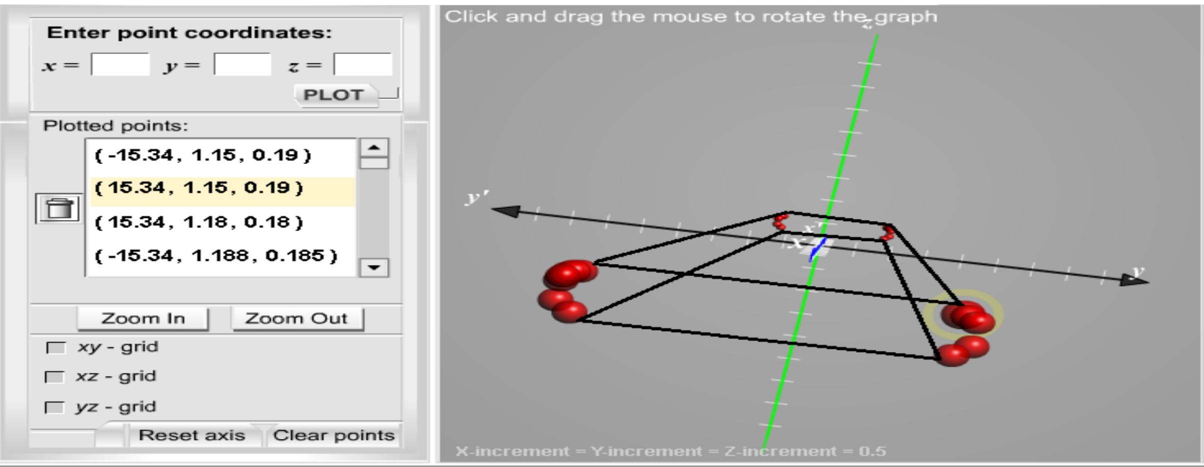

Figure 4 Edge points of the deck with the top right one highlighted

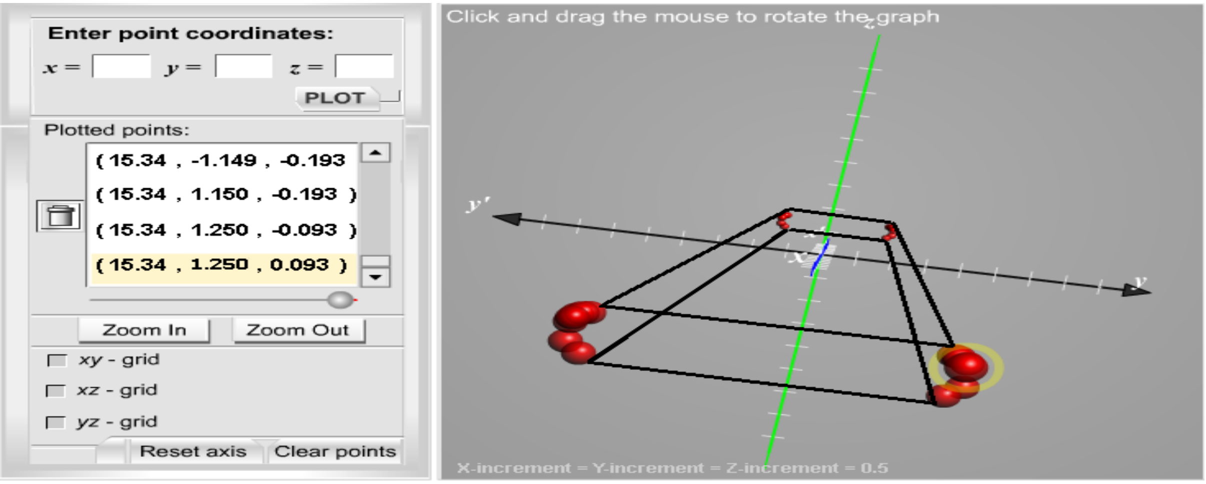

Figure 5 Edge points of the deck with the right most one highlighted

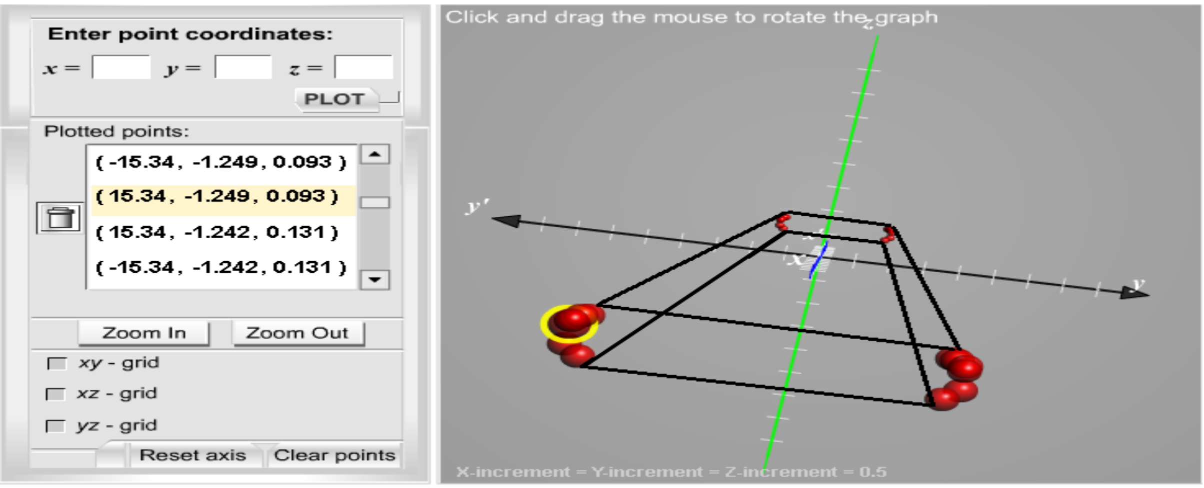

Figure 6 Edge points of the deck with the left most one highlighted

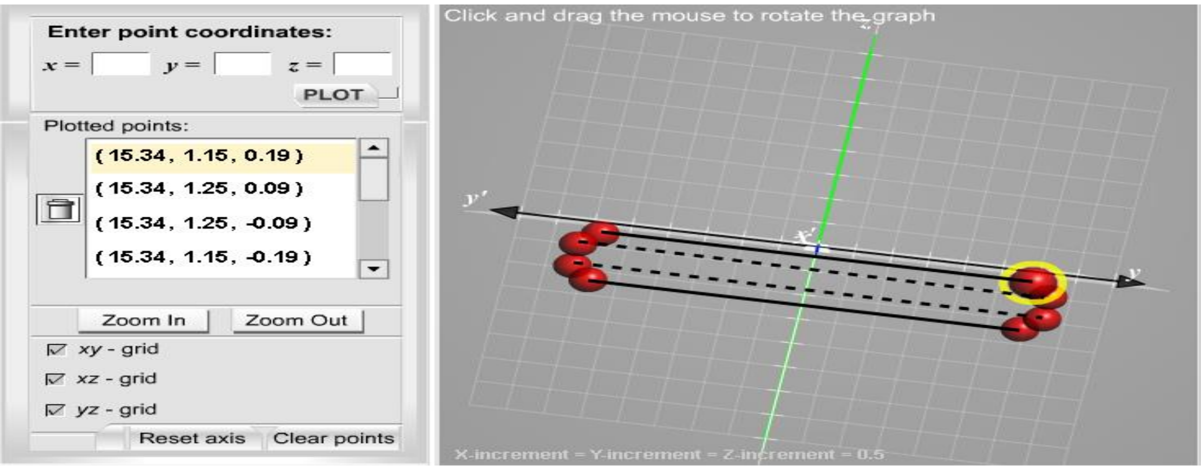

Figure 7 Cross section of the bridge deck and the horizontal stripes

For the solid cone frustum-shaped bridge pier with different top and bottom radius in the simple bridge model, the main geometry was represented by an IFCStyledItem. The IFCStyledItem instance was further represented by a total of 18 poly loops and 33 Cartesian points. Among these 33 Cartesian points, the ones with least and greatest Z values are the edge points, as shown in Figures 8 and 9. After the edge points of the circles are identified, Equation (1) can be used to calculate the radius of both circles.

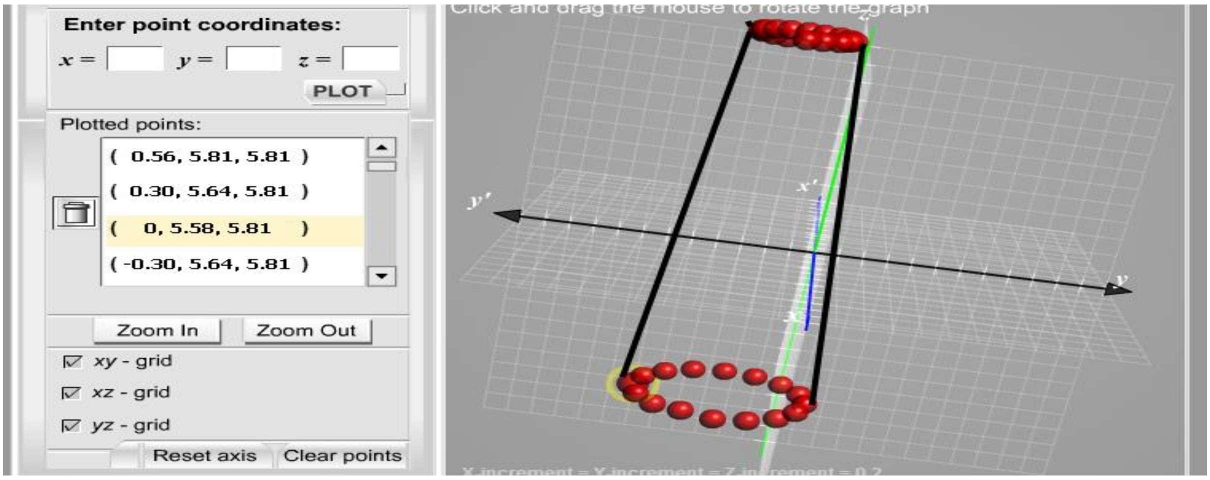

Figure 8 Edge points of a pier with the bottom left one highlighted

Consider Cartesian points with the least Z value, out of these points two edge points of the large circle can be identified by finding the least and greatest Y values (Figures 8 & 9). The distance between them is the radius (*R*) of the large circle. The radius (*r*) of the small circle can be found in a similar way. Moreover, using the difference in Z values of the edge points at the top and bottom, the height (*h*) of the pier can be calculated. Equation (3) can then be used for finding the volume of the pier, where *R* and *r* are the radiuses for the large and small circle, and *h* is the height of the pier.

$$Cone\ Frustum\ Volume\ V = \frac{\pi h}{3}(R^2 + Rr + r^2) \quad (3)$$

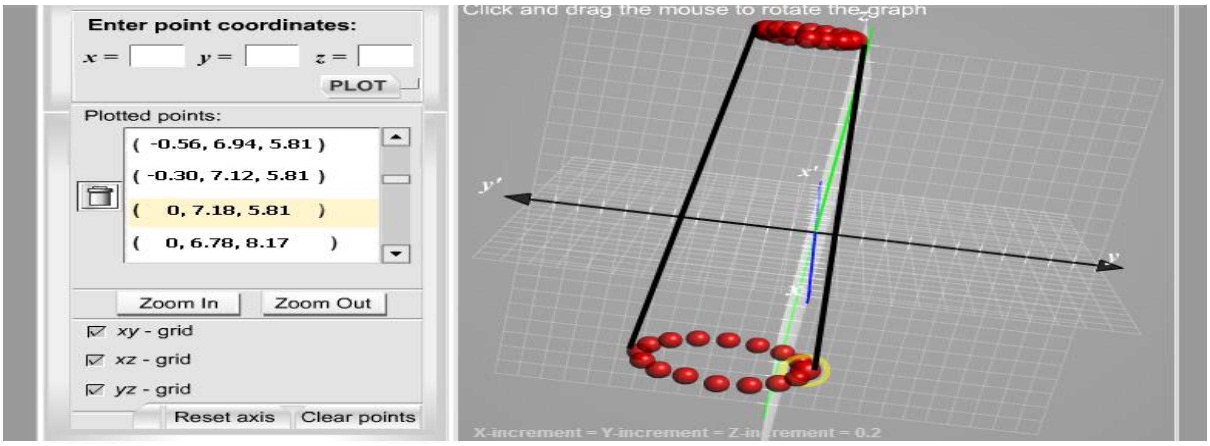

Figure 9 Edge points of a pier with the bottom right one highlighted

3.4 Step 4 - Test the quantity takeoff algorithms on unseen data

This step tests the developed quantity takeoff algorithms from Step 3. The algorithms are tested on unseen data that are created following the same workflow as the data used in algorithm development. For example, to assess the performance of the developed algorithms for bridge deck and piers, another bridge model (i.e., the testing model) was used. The testing model was created using the same workflow as was used in creating the development model. The developed quantity takeoff algorithms were implemented in Java programs and directly applied to the bridge deck and piers of the testing model. As a result, the developed quantity takeoff algorithms successfully extracted the necessary Cartesian points from the IFC file of the testing model and took off the quantities. As shown in Table 1 & 2, the quantities taken off by the algorithms were consistent with those manually extracted by the authors (with minor difference due to rounding errors).

Table 1: Experimental results for the bridge deck of the testing model

Measure	Length (ft.)	Width (ft.)	Thickness (ft.)	Cross sectional area (sq. ft.)	Volume (cu ft.)
Value by Algorithm	30.69	2.50	0.38	0.94	29.03
Value by Manual Extraction	30.69	2.50	0.38	0.94	29.05

Table 2: Experimental results for a bridge pier of the testing model

Measure	Large Radius (ft.)	Small Radius (ft.)	Height (ft.)	Volume (cu ft.)
Value by Algorithm	0.80	0.39	2.40	2.81
Value by Manual Extraction	0.80	0.40	2.36	2.76

4 Experimental Testing for Robustness

To test the robustness of the proposed method and algorithms, an experiment was conducted by applying the developed bridge deck and pier quantity takeoff algorithms to three other bridge models retrieved from different online sources. These three bridge models were in different original formats, namely, .dwg, .3ds, and .dgn. All the three models were converted into the IFC format for testing. Table 3 & 4 show the results of this experiment, where the developed algorithms generated consistent quantity results with manually extracted quantities. The small difference between those quantities for cross sectional area and volume were because of rounding errors. This results shows that the proposed method provides consistent results even for models from different formats (implying different model authoring workflows).

Table 3: Experimental results for robustness test of bridge deck quantity takeoff algorithm

Measure	Length (ft.)	Width (ft.)	Thickness (ft.)	Cross sectional area (sq. ft.)	Volume (cu ft.)
Value 1 by Algorithm	2.89	0.23	0.03	0.01	0.02
Value 1 by Manual Extraction	2.89	0.23	0.03	0.01	0.02
Value 2 by Algorithm	245.00	20.00	2.00	39.78	9747.41
Value 2 by Manual Extraction	245.00	20.00	2.00	39.90	9747.50
Value 3 by Algorithm	328.08	26.90	4.13	111.03	36428.42
Value 3 by Manual Extraction	328.08	26.90	4.13	111.01	36428.60

Table 4: Experimental results for robustness test of bridge pier quantity takeoff algorithm

Measure	Large Radius (ft.)	Small Radius (ft.)	Height (ft.)	Volume (cu ft.)
Value 1 by Algorithm	3.00	1.50	10.00	164.93
Value 1 by Manual Extraction	3.00	1.50	10.00	164.93
Value 2 by Algorithm	2.00	0.63	5.00	29.62
Value 2 by Manual Extraction	2.00	0.63	5.00	29.61
Value 3 by Algorithm	0.36	0.17	1.15	0.26
Value 3 by Manual Extraction	0.36	0.17	1.15	0.26

5 Contributions

In this paper, a new method is proposed for developing automated quantity takeoff algorithms from an IFC-based bridge model, in which geometric shape representation data (e.g., Cartesian point) in an IFC model are directly used for quantity takeoff purpose. The method enables a fast development of automated quantity takeoff algorithms that reduces the amount of manual effort needed for quantity input into IFC-based bridge models, therefore pushes the automation of IFC-based bridge cost estimation one step further.

The developed algorithm for each type of building object is reusable for the same type of object in any project using the same IFC schema. Any potential information changes during the import/export of building models between different software applications can be readily taken into consideration, as long as the modeling workflow remains the same. In addition, the proposed method is expected to work for any type of model authoring workflow based on the premise that at some point in the workflow the model can be converted into the IFC format.

Therefore, the proposed method not only lays a foundation for developing BIM-based bridge quantity takeoff applications, but also establishes a feasible approach to encompassing the IFC standard for satisfying any existing BIM-based bridge modeling workflow.

6 Conclusions and Future Work

In order to address the gap of leveraging inherent geometric representation of bridge components in an IFC model for quantity takeoff, therefore reducing the manual efforts involved in model preparation and processing for bridge cost estimation, this paper presented a new IFC-based method to generate automated quantity takeoff algorithms for a selected type of bridge component. The proposed method analyzes the internal geometric representation of a selected bridge component and generates an automated quantity takeoff algorithm leveraging Cartesian points and simple geometric formulae. The proposed method was applied to a simple bridge model created in MicroStation V6 software and exported into the IFC format. An algorithm for taking off quantity from a solid slab-shaped bridge deck, and an algorithm for taking off quantity from a solid cone frustum-shaped bridge pier were developed as a result. These two algorithms successfully extracted linear, areal, and volumetric quantities from another testing bridge model. The two algorithms also successfully extracted quantities from three other bridge models retrieved online that were originally in different formats. The results showed that the developed algorithm generated for each type of bridge object was reusable and effective even for models from different types of workflows. Any potential information changes during the import/export of building models between different software applications can be readily taken into consideration. The method presented not only lays a foundation for developing BIM-based automated bridge quantity takeoff applications, but also establishes a feasible approach to encompassing the IFC standard to satisfy any existing BIM-based bridge modeling workflow. It is also expected to be easily adaptable to other types of construction projects such as building projects.

Two limitations are acknowledged: (1) The proposed method currently only focuses on bridge components whose geometric shapes were known. Although selected types of bridge components can always be extracted based on visual recognition, how to automatically recognize the different shapes of bridge elements need to be investigated to further improve the automation of cost estimation. (2) The generated quantity takeoff algorithms in this paper are based on the assumption that the pose of the bridge is vertical (or with negligible tilts). If this assumption does not hold, the generated algorithms need to be improved using more delicate mathematical formulae to make them more robust. In future work, the authors plan to continue testing and enhancing the proposed method to help reduce the manual efforts needed in bridge cost estimation.

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