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Cartesian Points Visualization in Game Simulation for Analyzing Geometric Representations of AEC Objects in IFC

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Abstract –

Industry foundation classes (IFC) is widely accepted as a promising standard for building information modeling (BIM). IFC data can be processed with many open toolkits such as IfcOpenShell and java standard data access interface (JSDAI), which greatly supports BIM research and technology development. However, IFC data is not intuitive and requires training to understand it fully. As the core of almost any IFC data, understanding geometric representation is critical in most BIM research and technology development. The official IFC schema specifications provide detailed explanations of entities and attributes in IFC, which are helpful for gaining such understanding. However, understanding the explanations in the specifications requires certain knowledge and background. To facilitate an easier understanding of IFC data and to promote a wider adoption of IFC-based BIM, in this paper, an interactive visualization of the formation of fundamental 3D representations of a selected architecture, engineering, and construction (AEC) object was created in game simulation in a first-person view. The interactive simulation can help people gain understanding of 3D geometric formation and representation in IFC in an intuitive and speedy manner, which is expected to achieve retention of such knowledge comparable to or better than the conventional way of reading the specifications. The visualization was tested by 14 volunteers in comparison to reading the IFC schema specifications. A survey based on the experiment showed that the game simulation-based visualization was significantly easier to understand and took significantly less time to understand comparing to reading the specifications.

Keywords –

BIM; IFC; Geometric Information; AEC Objects; Game Simulation; Visualization; Cartesian Points

1 Introduction

Building information modeling (BIM) is a "data rich digital representation cataloging the physical and functional characteristics of design and construction" [1]. It is expected to serve as "a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle from inception onward" [2]. Since its inception BIM has been used for various purposes such as 3D coordination, 4D modeling, design reviews, as-built conditions modeling, structural analysis, energy analysis, cost estimation, sustainability evaluation, lighting analysis, and asset management [3]. For each of these purposes there are multiple (if not many) software applications to use, which benefited project stakeholders by reducing errors, time, and cost, improving quality, safety, profitability, and facilitating collaborations [4]. BIM applications are intended to be interoperable by definition, meaning that these applications should be able to "exchange information and to use the information that has been exchanged" [5]. However, a seamless interoperability between BIM applications is far from reality. Information missing and information inconsistency is not uncommon when BIM is exported from one application and imported into another. Even BIM applications from the same software provider may not have fully seamless interoperability [6] [7]. Such a lack of BIM interoperability costed the architecture, engineering, and construction (AEC) industry $15.8 billion annually [8].

In North America, the adoption of BIM in the AEC industry increased from 28% in 2007 to 71% in 2012 and is continuing to increase [4]. With the increased adoption of BIM, the lack of interoperability between BIM applications is only becoming a bigger problem, as was evidenced by a survey of contractors which showed that almost half (46%) of contractors with heavy software use considered the need of improving BIM interoperability to be of high/very high importance [4].

Standardization is one potential solution for BIM interoperability. Two main standardization efforts are industry foundation classes (IFC) and the CIMSteel Integration Standards Version 2 (CIS/2) [9]. While CIS/2 focuses on exchangeable data representation and information modeling for structural steel type of projects [10], the IFC standard is designed to be able to represent any type of building construction projects. IFC is an open and neutral data standard that is registered as an international standard ISO 16739 [11]. IFC has been widely accepted as the most promising data standard to solve BIM interoperability. IFC is dominating BIM research in academia and almost all main BIM software applications claimed to be compatible with IFC (i.e., through exportation and/or importation). Since its inception in 1997, IFC has been going through eight main release versions (IFC1.0, IFC1.5, IFC2.0, IFC2x, IFC2x2, IFC2x3, IFC2x3_TC1, IFC4) and is still under development towards IFC5, which is planned to extend to represent not only building projects but also infrastructure projects such as roadways and bridges. It stimulated a national trend in the U.S. towards civil integrated management (CIM) which is about implementing the same life cycle information management idea of BIM from vertical building projects to horizontal infrastructure projects [12]. Therefore IFC is attracting great attention in all sectors from academia, industry, and government. Some familiarity and understanding of IFC data is gradually becoming necessary for practitioners in the AEC industry, therefore IFC contents are entering the curriculum of construction education and training.

In spite of the openness of IFC standard, data instance files using IFC schema are not directly understandable like a bar chart. As of the current version IFC4, the IFC schema includes more than 750 entities and more than 350 types [13]. Each entity has its own specifications that define its attributes and allowed value assignments to the attributes. In an effort to limit the size of IFC instance files, cross referencing is used ubiquitously where one entity instance can refer to another entity instance as the value of one of its attribute. It takes a certain level of training to understand IFC data, and the learning curve is not steep. For example, in a graduate level class taught by the first author, it took a significant portion of a lecture's time to explain the intricacies of the IFC data.

Geometric information is an essential part of any BIM data, and it is a critical part of any IFC data files. Entity instances that represent geometric information can take a significant portion of an IFC instance file. For example, "in the 'Duplex Apartment' IFC data published by buildingSMARTalliance of the National Institute of Building Sciences [14], more than 71.6% (27,866 out of 38,898) of the entities were directly used for representing geometric information." [15]. Therefore, IFC data cannot be fully understood without understanding its geometric information representations.

Cartesian points are the most fundamental elements for representing geometric information in IFC data, they play critical roles in the interchange of information between as-built model and as-design model, and from as-design model to advanced visualization platforms such as game simulation and virtual reality platforms. To help understand geometric representations using Cartesian points in IFC data, the authors proposed the use of a new game simulation-based interactive visualization. The remaining sections of this paper describe the background of this visualization technique, the details of an example using this visualization and its testing results and analysis.

2 Background

This background section introduces background knowledge in game simulation, industry foundation classes (IFC), and Cartesian points in IFC.

2.1 Game Simulation

The concept of game simulation is a combination of the concept of game and the concept of simulation. The key elements of a game are rules and goals, interaction and feedback, challenge and strategies, and motivation and fun [16] [17]. The key elements of a simulation are model of reality, abstract concepts, interaction, experiment, decisions from a specific angle of view, and purposeful testing [17]. Therefore interactions from a specific role or angle of view is an essential element of a game simulation. Game simulation has been shown to be an effective teaching tool, based on the two assumptions that "practice improves one's ability to perform" and "simulations provide students with opportunities to practice making management decisions in a safe environment" [18].

Game simulation has been widely used in AEC research to help with construction engineering and management education [17][19], architectural design review [20] [21] [22], mechanical, electrical, and plumbing (MEP) design and analysis [23], facility management [24] [25], constructability and productivity analysis [26], and construction operation/safety training [27] [28].

There are multiple game engines available off-the-shelf such as Unity3D, Unreal Engine, and CryENGINE. Game simulations using these game engines may well use information from BIM especially geometric information, through intermediate format transfers such as FBX and OBJ files. Cartesian points lay the foundation of geometric information representation in these formats. For example, Figure 1 shows the starting section of an OBJ file that represents the geometry of a bent wood

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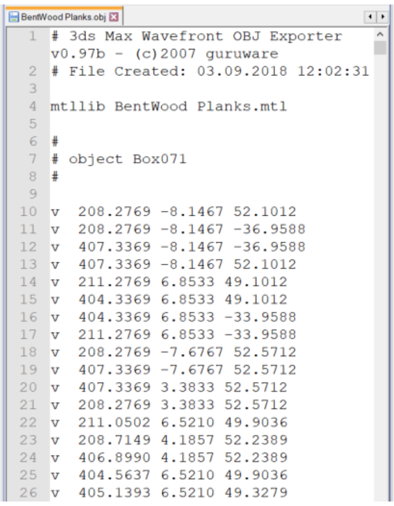
plank. While the lines starting with # indicate comments, each line that starts with a “v” is representing the x,y,z coordinates of one Cartesian point.



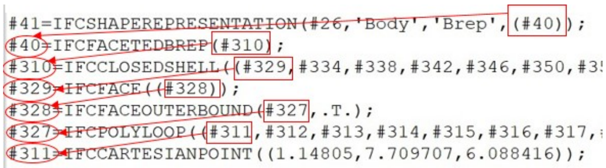
```
# 3ds Max Wavefront OBJ Exporter
v0.97b - (c)2007 guruware
# File Created: 03.09.2018 12:02:31

mtllib BentWood Planks.mtl

#
# object Box071
#

v  208.2769 -8.1467 52.1012
v  208.2769 -8.1467 -36.9588
v  407.3369 -8.1467 -36.9588
v  407.3369 -8.1467 52.1012
v  211.2769 6.8533 49.1012
v  404.3369 6.8533 49.1012
v  404.3369 6.8533 -33.9588
v  211.2769 6.8533 -33.9588
v  208.2769 -7.6767 52.5712
v  407.3369 -7.6767 52.5712
v  407.3369 3.3833 52.5712
v  208.2769 3.3833 52.5712
v  211.0502 6.5210 49.9036
v  208.7149 4.1857 52.2389
v  406.8990 4.1857 52.2389
v  404.5637 6.5210 49.9036
v  405.1393 6.5210 49.3279
```

Figure 1. Starting section of an OBJ file

2.2 Industry Foundation Classes

Industry foundation classes (IFC) is an open and neutral data standard for building and construction industry data, and it is registered as ISO 16739 since the IFC4 version [29]. IFC data files can be using one of three main formats - .ifc, .ifcXML, and .ifcZIP, which are the default, XML represented, and compressed formats, respectively. The default and XML represented formats are mainly used in BIM research, especially the default .ifc format. Because it is based on the STEP physical file structure which is according to another international standard ISO10303-21. There are many open sourced utilities that can be used to directly read/write .ifc files, such as IfcOpenShell, java standard data access interface (JSDAI), and IFC++.

In the IFC schema, entities and attributes of the entities are used to represent concepts and relations between or properties of concepts, respectively. For example, *IfcWallStandardCase* is an entity to represent a standard wall concept. The second attribute of *IfcWallStandardCase*, *OwnerHistory* is used to represent the relation between the standard wall and an owner history entity that is used to represent all history and identification related information of the standard wall. The third attribute of *IfcWallStandardCase*, *Name* is used to represent the name property of the standard wall. In the instantiated data files using the IFC schema, cross referencing is used between one entity instance and another to represent the relations between entity instances. For example, Figure 2 shows the partial view of an IFC instance file where six cross references were highlighted.



```
#41=IFCSHAPEREPRESENTATION(#26,'Body','Brep',(#40));
#40=IFCFACETEDBREP(#310);
#310=IFCCLOSEDSHELL((#329,#334,#338,#342,#346,#350,#3
#329=IFCFACE((#328));
#328=IFCFACEOUTERBOUND(#327,.T.);
#327=IFCPOLYLOOP((#311,#312,#313,#314,#315,#316,#317,
#311=IFCCARTESIANPOINT((1.14805,7.709707,6.088416));
```

Figure 2. An example partial IFC instance file

Geometric information is an important part of an IFC model. The mechanism for representing geometric information in IFC is based on an international standard ISO 10303-42 [11]. In spite of the standardization of the geometric representation, the geometric data in an IFC file is not intuitively understandable. One reason is the varieties of geometric representations in IFC, such as “Body” and “Axis” [30]. Another reason is the complexities within each type of geometric representation. For example, the solid model of a “Body” can be represented by “Swept Solids” “Boolean Results” or “Brep Bodies.” [31]. “Swept Solids” use the solid sweeping technic to form a 3D representation, i.e., planar bounded surfaces swept along a defined direction. “Boolean Results” take the union or intersection between two solids to define a new solid. “Brep Bodies” use boundary representations to represent a 3D shape where each boundary representation is a surface element. The IFC data in Figure 2 was using the “Brep Bodies” 3D geometric representation, which can be seen from the use of the entity *IfcFacetedBrep*. The *IfcClosedShell* is an entity to represent the 3D shape. Figure 3 summarizes the path from the *IfcClosedShell* to the lowest-level element *IfcCartesianPoint*. The boundaries of this *IfcClosedShell* are represented by multiple occurrences of *IfcFace*. The boundaries of the *IfcFace* are defined by *IfcFaceOuterBound*, whose boundaries, in turn, are defined by *IfcPolyLoop*. Finally, the definition of the *IfcPolyLoop* is achieved by using multiple occurrences of *IfcCartesianPoint*.

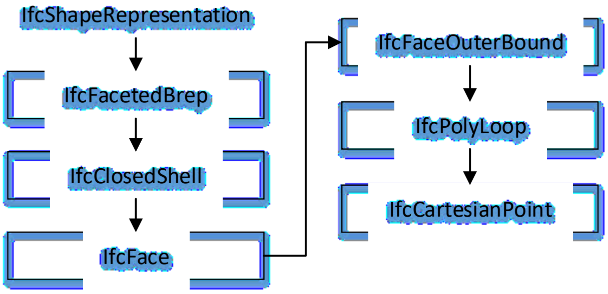


Figure 3. Summary of the pathway of a Brep geometric representation in IFC

2.3 Cartesian Points in IFC

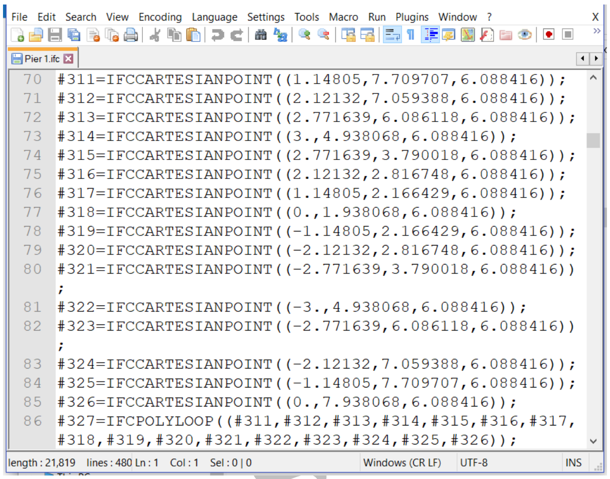
In spite of the variety of ways of representing geometric information in IFC, they all reduce to Cartesian points in the end. Therefore the understanding of Cartesian points is the key to the understanding of geometric information in IFC. Such an understanding is also important to the collective use of IFC model with other models such as as-built models [32], which can be collected using various sensing technologies such as laser scanning [33] and image sensing [34]. One classic use of as-built models together with as-designed models in IFC is to monitor the progress of construction, where matching Cartesian points from as-built point clouds and IFC data need to be performed manually and/or algorithmically [34] [35].

In the future use of robotics both in a built environment and in the construction of a built environment, the geometric information carried by an IFC model could foreseeably play critical roles. For example, IFC models have already been used in researching and developing indoor robotic navigation algorithms [36] [37]. IFC models have also been proposed to guide the use of robotic systems to automatically construct different types of structures such as concrete structure [38], masonry structure and prefabricated steel structure [39].

Due to the importance of geometric information representation in IFC, it is desirable to incorporate its introduction to modern AEC curriculum. In fact, in the first author's graduate level class titled "automation in construction management," a 3-hour lecture is designated to the introduction of BIM with a focus on IFC. There are also homework assignments, quizzes, and exams to enforce students' learning. However, such a devotion of time and efforts is not practical for all learners, especially for casual learners who just need to grasp a basic understanding of IFC data without too much detail. Unfortunately, IFC data was not designed this way. For example, Figure 4 shows partial data instances of an IFC file that represents a cone frustum-shaped bridge pier. All entity instances in Figure 4 except for the last one are representing Cartesian points, and the last entity instance is representing a poly loop that is defined using all the shown Cartesian points that are above it. It is not intuitively clear how these Cartesian points form the poly loop and it is not clear either where the poly loop fits in the cone frustum shape, even if a visualization of the cone frustum shape is given (Figure 5).

3 Proposed Method

To help casual learners grasp how Cartesian points were used to form and represent a 3D shape in IFC data, the authors propose a new interactive visualization method based on game simulation. Such method is also useful for serious learners to quickly grasp the idea before they go deeper in learning the details.



```
#311=IFCCARTESIANPOINT((1.14805,7.709707,6.088416));
#312=IFCCARTESIANPOINT((2.12132,7.059388,6.088416));
#313=IFCCARTESIANPOINT((2.771639,6.086118,6.088416));
#314=IFCCARTESIANPOINT((3.,4.938068,6.088416));
#315=IFCCARTESIANPOINT((2.771639,3.790018,6.088416));
#316=IFCCARTESIANPOINT((2.12132,2.816748,6.088416));
#317=IFCCARTESIANPOINT((1.14805,2.166429,6.088416));
#318=IFCCARTESIANPOINT((0.,1.938068,6.088416));
#319=IFCCARTESIANPOINT((-1.14805,2.166429,6.088416));
#320=IFCCARTESIANPOINT((-2.12132,2.816748,6.088416));
#321=IFCCARTESIANPOINT((-2.771639,3.790018,6.088416))
;
#322=IFCCARTESIANPOINT((-3.,4.938068,6.088416));
#323=IFCCARTESIANPOINT((-2.771639,6.086118,6.088416))
;
#324=IFCCARTESIANPOINT((-2.12132,7.059388,6.088416));
#325=IFCCARTESIANPOINT((-1.14805,7.709707,6.088416));
#326=IFCCARTESIANPOINT((0.,7.938068,6.088416));
#327=IFCPOLYLOOP((#311,#312,#313,#314,#315,#316,#317,
#318,#319,#320,#321,#322,#323,#324,#325,#326));
```

Figure 4. Cartesian points data from the geometric representation of a cone frustum shape in IFC

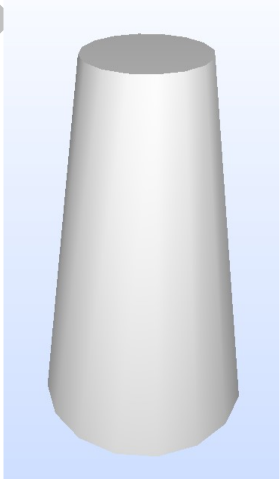


Figure 5. Visualization of a cone frustum shape

As shown in Figure 6, the proposed method uses an elemental cube to represent a Cartesian point and a colored line to represent a relation between one Cartesian point and another. In the time dimension, the Cartesian points and their connected relations are visualized one by one, following a sequence dictated by the order of these Cartesian points in the original structured IFC data instance file. This visualization can be observed from a first-person view, a third-person view, or any arbitrary angle of view as defined. The view can also be changed in real-time based on learners' preferences.

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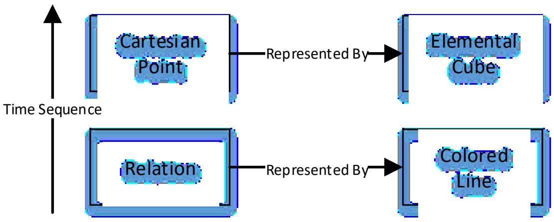

Figure 6. Proposed Cartesian point visualization method

4 Preliminary Experimental Testing

To test the effectiveness of the proposed method, a preliminary experiment was conducted by implementing the game simulation-based visualization of the cone frustum-shaped bridge pier object shown in Figure 5. The Cartesian points that represent the geometric information of the cone frustum shape were extracted manually from the source IFC instance file. The Unity3D game engine was used to implement the visualization based on the proposed method. The background was set to be an arbitrary white ground and a default blue sky. The visualization was created following a first-person view that can be adjusted in real-time based on the position and head orientation of the virtual observer. Figure 7 to Figure 10 show snapshots of the visualization during different stages of the game simulation, namely, the first Cartesian point, the first poly loop, side faces, and the completed shape. It can be seen that the virtual observer was observing from different angles of view in these snapshots.

Figure 7. Visualization of the first Cartesian point in a cone frustum shape

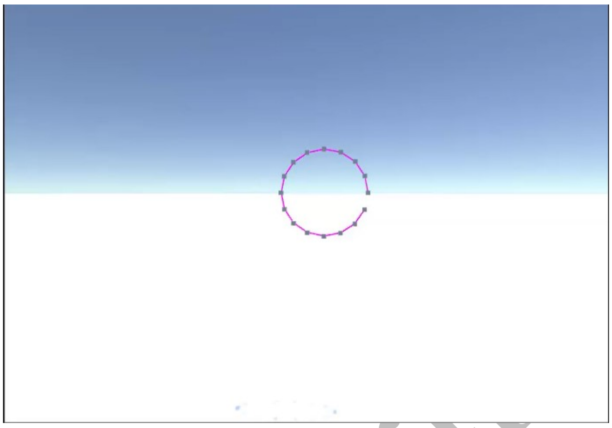

Figure 8. Visualization of the first poly loop in a cone frustum shape

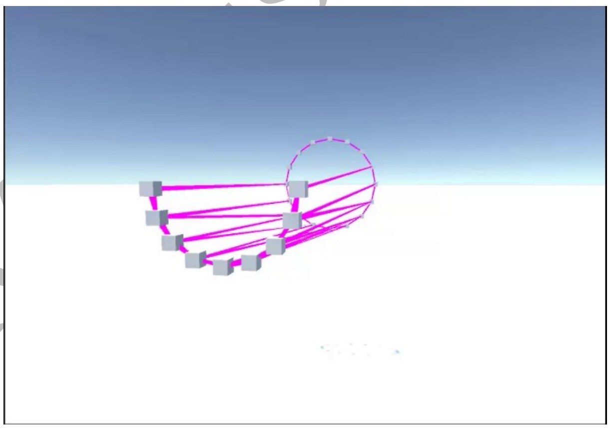

Figure 9. Visualization of side faces formed by Cartesian points in a cone frustum shape

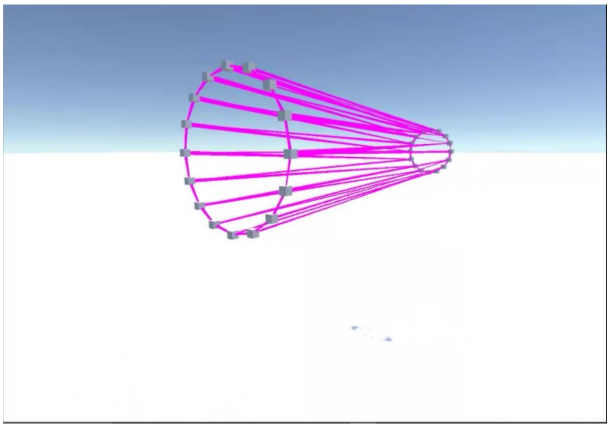

Figure 10. Visualization of the complete cone frustum shape formed by Cartesian points

The implemented visualization was tested by 14 graduate students at Purdue University and University of Florida, who all have some research experience in BIM (Table 1). The game simulation was given to the participants together with and in comparison with an explanation material based on IFC specifications. Half of the students were asked to start with the game-based simulation, and then move to the written explanation material; the other half of the students were asked to start with the written explanation material, and then move to the game-based simulation to reduce the effect of multiple-treatment interference with the results. The explanation material included: (1) an explanation of the goal, (2) visualization of the cone frustum shape (Figure 5), (3) geometric representation of the cone frustum shape in raw IFC data (Figure 2; Figure 4), and (4) official explanations of the entities by buildingSMART.

Table 1. Participants' information

BIM research experience	Number of Participants
1 Year or Less	4
1-2 Years	4
2-3 Years	2
3 Years and above	4

5 Experimental Results and Discussion

The experimental results were shown in Table 2. The scale levels are: 1-Very difficult, 2-Difficult, 3-Neutral, 4-Easy, 5-Very easy. The maximum score, minimum score, and mean score for the easiness of understanding of the written explanation material were 3, 1, and 1.79, respectively. The maximum score, minimum score, and mean score for the easiness of understanding of the game simulation-based visualization were 5, 3, and 4.00, respectively. The game simulation-based visualization was much easier to understand than the written explanation material and the difference was significant at 99.9% confidence level based on paired t-test. The time taken to understand the written explanation material had a maximum, minimum, and mean values of 1,680(s), 225(s), and 545.89(s), respectively. The time taken to understand the game simulation-based visualization had a maximum, minimum, and mean values of 480(s), 80(s), and 130.37(s), respectively. It took much less time to understand the game simulation-based visualization than that in understanding the written explanation material and the difference was significant at 99.9% confidence level.

Some comments received during the test were: (1) the written explanation material was difficult to understand because of the needed background knowledge, (2) a slower speed in the visualization would make it easier to follow and understand, (3) the explanation material could be used to complement the visualization, and (4) adding audio to the visualization would make learners' understanding even easier.

Table 2. Easiness of understanding results

	Explanation material			Game simulation-based visualization		
	min	mean	max	min	mean	max
Easiness of understanding	1	1.79	3	3	4.00	5
Time taken to understand (*s*)	225	545.89	1,680	80	130.37	480

6 Conclusion

With the fast development and adoption of building information modeling (BIM), the demand in learning industry foundation classes (IFC) data – the ISO registered data standard of BIM, is increasing. In this paper, the authors proposed the use of a new method to help people learn the formation of geometric representations using Cartesian points in IFC data. The new method is based on game simulation technology and visualizing the Cartesian points and relations between the points in sequence. The new method was evaluated in a preliminary test where a cone frustum-shaped bridge component represented in IFC was presented using the method to 14 test participants. At the same time a written explanation of the same knowledge was provided to the participants. Collected results showed that the game simulation-based visualization was significantly easier to understand and took significantly less time to understand comparing to reading the explanation material.

7 Contributions to the Body of Knowledge

This paper contributes to the body of knowledge in that it is the first time that game simulation in first person view was used to help with understanding of geometric representation of IFC data with a focus on Cartesian points and the comparative effects were tested with respect to a written explanation material in a quantitative manner.

8 Limitations and Future Work

Two main limitations are acknowledged. In spite of the novelty of the proposed method, the test was only conducted on one shape and with a limited set of participants. More testing on more shapes and participants are needed to make the results more robust. The test was only conducted on first-person view, how other angles of views affect the understanding need to be further explored. In future work, the authors plan to extend the test to cover more shapes, more participants, and more angles of views.

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