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A PROCESS TO DIVIDE CURVED WALLS IN IFC-BIM INTO SEGMENTED STRAIGHT WALLS FOR BUILDING ENERGY ANALYSIS

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Abstract. The amount of energy that buildings consume is currently attracting significant interest throughout the world, and considerable attention is being devoted to the development of green buildings to reduce energy consumption; however, the current process being used to conduct building energy analysis has a significant shortcoming in that it cannot directly use building information modelling (BIM)-based representational data that includes a curved wall. Currently, the curved wall must be converted into segmented straight walls (SSWs) in the building model in order for the building energy analysis (BEA) program to be able to recognize and use the data. In this paper, we have proposed a segmentation process for curved walls in industry foundation classes (IFC)-based BIM for BEA. The proposed process consists of three sub-processes: 1) extracting data from the IFC model; 2) dividing the curved wall into several segmented straight walls; and 3) generating an INP file as a building description for DOE-2.2-based BEA. The proposed process will enable the engineers who are responsible for BEA to use a BIM-based model directly in the BEA program without having to do additional work. The proposed process can help ensure that the BEA results are accurate and reliable.

Keywords: BIM, building energy analysis, IFC, curved wall, representation data.

Introduction

Since the energy consumption of buildings continues to increase, the use of building energy analysis (BEA) to simulate building energy consumption has become an important issue worldwide. In the last decade, extensive research related to BEA has been conducted using various methodologies. Schlueter and Thesseling (2009) proposed a BEA approach that considered the thermo-economic concept of exergy in alternative designs. Exergy analysis takes into account the overall available energy (Shukuya, Hammache 2002). Kim *et al.* (2011) suggested a BEA approach that used data mining to determine useful patterns for improving energy efficiency during the design phase. And Kim and Yu (2013a) proposed a material name-matching system using ontology to automatically add the thermal properties of construction materials.

BEA systems have also been developed with building information modelling (BIM) technology. Since BIM technology has been used in architecture, engineering, and contracting (AEC) industry, a 3D-based building model can be used in the BEA process; using a BIM-based BEA system allows the engineer to easily and accurately calculate or simulate the energy consumption of a building (Laine, Karola 2007; Woo *et al.* 2011; Dziugaite-Tumeniene *et al.* 2012; Oh *et al.* 2011; Venckus *et al.* 2012; Ali 2004). However, since there is a problem related to the interoperability of data between BIM-based design software and the BEA system, the 3D model, in general, must be checked and remodelled by the BEA engineer (Maile *et al.* 2007). To that end, in 2000, the green building XML (gbXML) file format was developed for the BEA process. Since gbXML supports 3D models, BIM-based BEA systems can be used in several applications (Hygh *et al.* 2012; Pratt *et al.* 2012). However, as some BIM-based design programs cannot export the building model in gbXML directly, the engineer must remodel the building model through the use of other software that supports the gbXML file.

One of the most widely-used BEA engines in the world is the DOE-2.2 engine; however, since the BEA engine cannot support a complex building model, a specific algorithm is necessary to analyze a complex building model, and researchers have attempted to analyze complex building models (Sun *et al.* 2002; Tang *et al.* 2006; Monstvilas *et al.* 2012; Suter, Mahdavi 2004; Kim, Yu 2013b). Previous research, however, has been limited

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in that a specific system or mathematical algorithm must be used that lacks data interoperability with other BEA tools. Thus, engineers may be required to use a specific tool with which they have no experience in the process of implementing a building model that involves complex geometry.

There are a few approaches to analysing the energy consumption of a building model that include curved walls. The first approach is to rebuild a building model for the purpose of energy analysis into a BEA program (e.g. ECOTECT or eQUEST). In this case, an engineer must segment a curved wall into a series of straight walls, because most of the BEA programs cannot process curved wall data (Miller 2010). The second approach is to use an add-on program (e.g. AUTODESK 360 Energy analysis or EcoDesigner) on a BIM authorizing program (e.g. Revit or ArchiCAD). This is a very simple and succinct approach, but it has limitations in regard to the interoperability of the building model. The third approach is to use the gbXML file of a building model. As the gbXML file format is designed only for BEA, it is widely known that using a gbXML file is a de-facto standard for BEA; however, if we can extract all the required data for BEA from an IFC file, it is much more effective to use an IFC file than to handle other formats, such as gbXML.

To solve these problems, we propose a process for dividing curved walls in IFC into segmented straight walls (SSWs) for the BEA process. In the process, a curved wall is divided into a number of SSWs by calculating the coordinates using trigonometric functions. Since the proposed process adopts the IFC file as an input, it is not necessary to generate any additional building model for the BEA process. The proposed process consists of three sub-processes: 1) extracting data from the IFC model; 2) dividing the curved wall into several SSWs; and 3) generating an INP file. Further, if the sub-processes are computerized, the process of segmenting a curved wall into SSWs can be automatically implemented.

In this paper, we have limited curved walls to those that arc along their footprint, avoiding elliptical and free-form curves. In addition, the representation data are referenced by the "basiscurve" attribute of the IfcCircle entity from the IFC schema as a curved wall. The DOE-2.2 engine is used in this study as the BEA engine, so the format of the building description is the INP file format.

1. Required data

In this paper, we focused on the representation data of a curved wall in the IFC model's data. For this reason, when a curved wall is created by a BIM-based design tool, the representation data is stored in specific data entities. Before the data can be used in the proposed process, these data entities must be defined. The following contexts show the representation data of the specific data entities in the IFC schema.

A curved wall has the attributes of the IfcWall entity in the IFC schema. There are many attributes for the IfcWall, but the Representation and ObjectPlacement data are the most important data related to the proposed process. The data for ObjectPlacement are related to the 3D-based coordinates of the relative coordinate system (RCS) that is called the X'-Y' system. In this paper, the Ifc Axis 2 Placement 3D entity is done through the IfcObjectPlacement entity.

There is an angle value (θ_R) between the X-Y and X'-Y' systems. In addition, the representation data of a curved wall, as its shape information, are created by the basis curve (according to the IfcCircle entity in the IFC schema) to relate IfcShaperep Resentation through the IfcProduct Representation entity. Some data are required to develop the proposed process, as shown in Figure 1 and listed below:

1. X-Y system

X-Y system refers to the absolute coordinate system (ACS) that defines the location of the building elements on the IFC schema. In this paper, the X-Y system faces the X'-Y' system as an RCS.

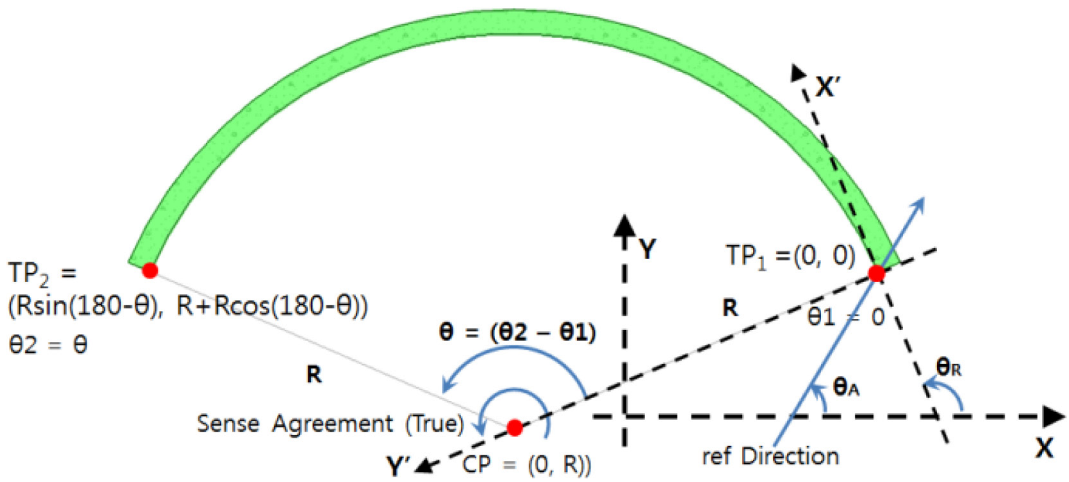

Fig. 1. Definitions of required data on proposed process

2. X'-Y' system

The X'Y' system refers to the RCS that defines the representation of the curved wall according to the IfcCircle entity.

3. Center Point (CP)

CP is the center point of the circle that defines the shape of a curved wall. CP exists on the Y' axis in the X'-Y' system, as shown in Figure 1. If the radius of the circle is R, CP is located by (0, R) in the X'-Y' system.

4. Trimmed Point (TP1)

TP1 is the starting point of the reference line of a curved wall. In general, TP1 is located at the zero point (0, 0) in the X'-Y' system to define the reference line of a curved wall.

5. Trimmed Point (TP2)

TP2 is an end point of the reference line of a curved wall in the X'-Y' system.

6. Radius value (R)

R is the radius of the circular sector of a reference line of a curved wall. It is extracted from the IfcCircle entity.

7. Trimmed angle1 (θ1)

θ1 is the angle between the zero point and TP1 in the X'-Y' system: it can be extracted from the IfcParameterValue of IfcTrimmedCurve through the Time1 attribute.

8. Trimmed angle2 (θ2)

θ2 is the angle between the zero point and TP2 in the X'-Y' system.

9. θ

θ is an angle that is related to the center point of a circular sector. In the proposed process, θ is calculated by Eqn (1):

$$\theta = \theta 2 - \theta 1. \quad (1)$$

10. Rotation angle value between systems (R)

θR is the angle of the element representation between the X-Y and X'-Y' systems to locate the elements on the X-Y system according to the angle of the X and X' axes.

11. Rotation angle value with location data (θA)

θA is the angle of element placement. When the element location is defined by the IFC schema, the angles of the ObjectPlacement and Representaion attributes of a building element must be considered.

12. Sense Agreement

Sense Agreement is the standard direction of an angle to measure the rotation of an angle in the IFC schema. In general, "False" connotes a clockwise direction, and "True" means a counter clockwise direction.

13. Location coordinates

Location coordinates are the data of coordinates that define where the element is placed on the X-Y system. They consist of X, Y, and Z axis values.

14. Depth

Depth is the wall height data value of the curved wall. The depth data are contained as representation data.

2. Proposed process

2.1. Overall process

To divide a curved wall into several (i.e. n) SSWs, the overall proposed process is shown in Figure 3. The process proposed in Figure 3 is comprised of three sub-processes. First, the related data are extracted from the IFC file using a specific entity. The extracted data are stored to the BIM object DB to use in the other procedures. Based on the extracted data of the BIM object DB, segmented straight wall points in the RCS ($SSWPR_n$) are created by the process of point rotation using trigonometric functions. Then, $SSWPR_n$ is converted into segmented straight wall points in the ACS ($SSWPA_n$) by a specific mathematical formula using the values of θR and θA. Segmented straight walls (SSW_n) are defined by connecting each $SSWPA_n$. The INP file is generated by the created SSW_n s, including the attributes of the original curved wall, such as the materials used, thickness, and building story.

2.2. Process of extracting data from IFC

To extract the required data of the proposed algorithm, several data entities are parsed, including IfcWall and IfcTrimmedCurve. Both entities are related to each other by relationships of reference. For example, the representation data of IfcWall are contained in IfcShape Representation as a polygon. If the wall is curved, the polygon is expressed by the IfcTrimmedCurve entity as a relationship of reference. At first, the system searches IfcWall entities in the IFC file. If the IfcWall entity has the IfcTrimmedCurve attribute in the representation data, the wall is curved. Then, Sense Agreement data value can be extracted from the IfcTrimmedCurve entity. The CP, R, θR, TP1, θ1, TP2, and θ2 data also can be extracted from the IfcTrimmedCurve entity. In addition, the location coordinates, θA, and the depth data can be extracted from the representation data of the IfcWall entity. The data extraction sub-process is shown in Figure 4.

2.3. Process of dividing curved walls

2.3.1. Process of creating $SSWPR_n$

First, the angle value θ is calculated through θ2 of Trim2 and θ1 of Trim1 as the IfcParameter Value from BIM object DB (Eqn (1)). Using the value of Sense agreement, the direction of θ is defined, and, if the value of Sense agreement is false, the direction of θ is changed by "– θ". Then, the number of SSWs provided as input to calculate the coordinates of $SSWPR_n$ is the "n" value, which should be larger than 2. Then, the coordinates of TP_1 are determined. If there is no TP_1 on the BIM object DB at this time, then TP_1 has not been extracted from IFC, and TP_1 is obtained by Eqn (2), using CP of the IfcCircle. In general, the coordinates of CP are (0, R):

$$TP_1 = CP\ (a0,b0) + (0,-R). \quad (2)$$

To calculate the coordinates of $SSWPR_n$, we rotate the coordinates of TP_1 to the zero point in the X'-Y' sys-

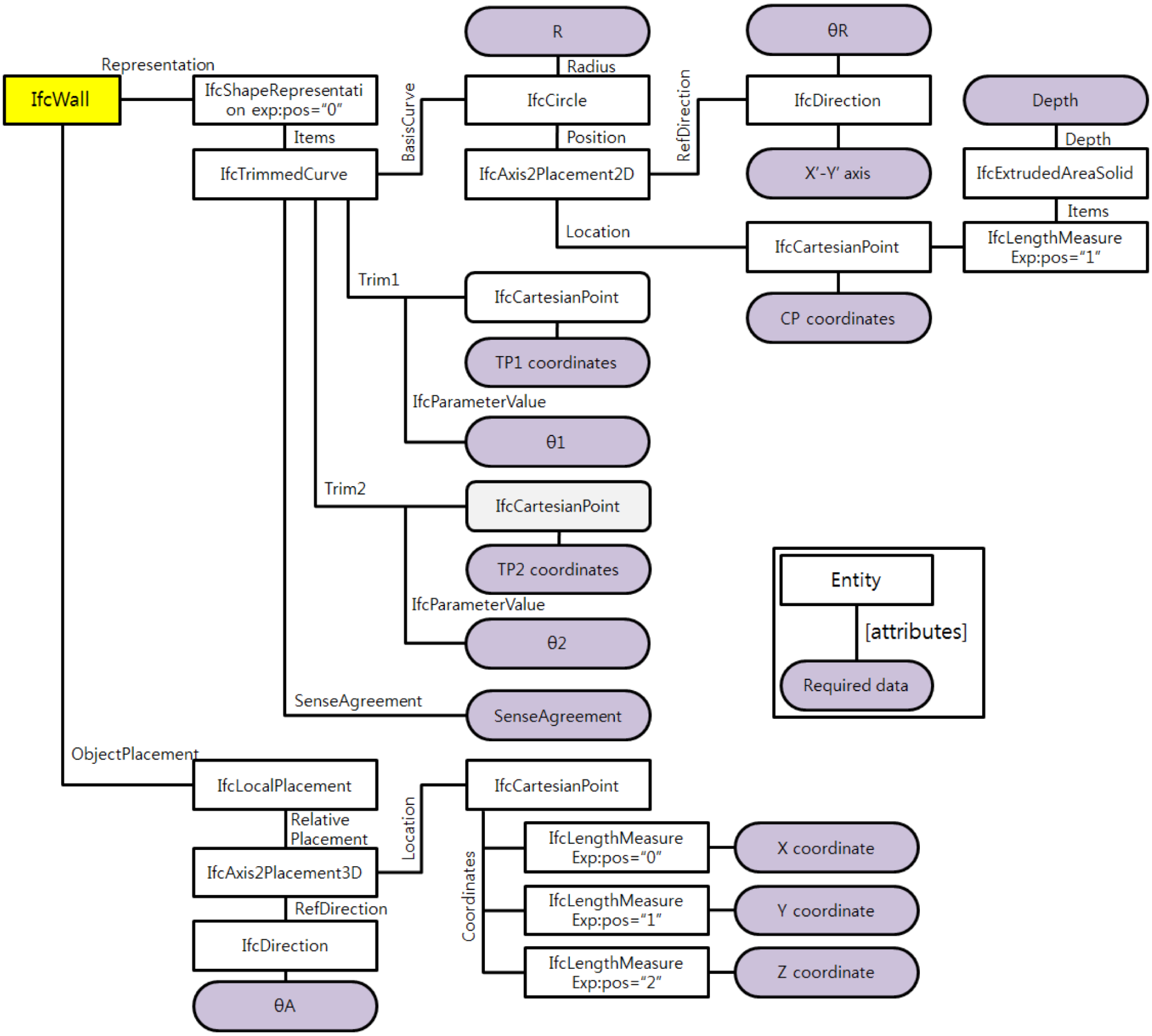

Fig. 2. Data extraction path in IFC

tem. To that end, CP is moved to the zero point using Eqns (3) and (4), and it is designated as CP'. At this time, all of the extracted coordinates are also moved the same distance:

$$CP' = CP\,(a0,b0) - CP\,(a0,b0) = (0,0); \qquad (3)$$

$$TP_1' = TP_1\,(a\,1, b\,1) - CP(a\,0, b\,0) = (0, -R). \qquad (4)$$

Next, θ is divided by n to calculate the rotation angle of TP_1'. Using the rotation angle, TP_1' is rotated by θ/n in the direction of θ n times using Eqns (5) and (6), designated as $SSWPR_n$ (Fig. 5). When k becomes equal to n, the coordinates of $SSWPR_n$ are the same as TP_2':

$$x_k = \left(x_{k-1} \times \cos\frac{\theta}{n}\right) - \left(y_{k-1} \times \sin\frac{\theta}{n}\right); \qquad (5)$$

$$y_k = \left(x_{k-1} \times \sin\frac{\theta}{n}\right) - \left(y_{k-1} \times \cos\frac{\theta}{n}\right). \qquad (6)$$

The process of creating $SSWPR_n$ using representation data from the IFC model is shown in Figure 6.

2.3.2. Process of creating $SSWPA_n$

Since $SSWPA_n$ are created in the X'-Y' system, $SSWPA_n$ must be converted to the X-Y system as the ACS. Before doing so, the angle of rotation between X'-Y' and X-Y is defined by Eqn (7):

$$\text{The angle value of system rotation} = \theta A + \theta R. \qquad (7)$$

The $SSWPR_n$ can be rotated with Eqn (7) to convert it to $SSWPA_n$ as Eqns (8) and (9):

$$X_k = \left(x_k \times \cos\left(\theta A + \theta R\right)\right) - \left(y_k \times \sin\left(\theta A + \theta\right)\right); \qquad (8)$$

$$Y_k = \left(x_k \times \sin\left(\theta A + \theta R\right)\right) - \left(y_k \times \cos\left(\theta A + \theta\right)\right). \qquad (9)$$

The $SSWPA_n'$ are located in the X-Y system, but not in the original location of the curved wall. Thus,

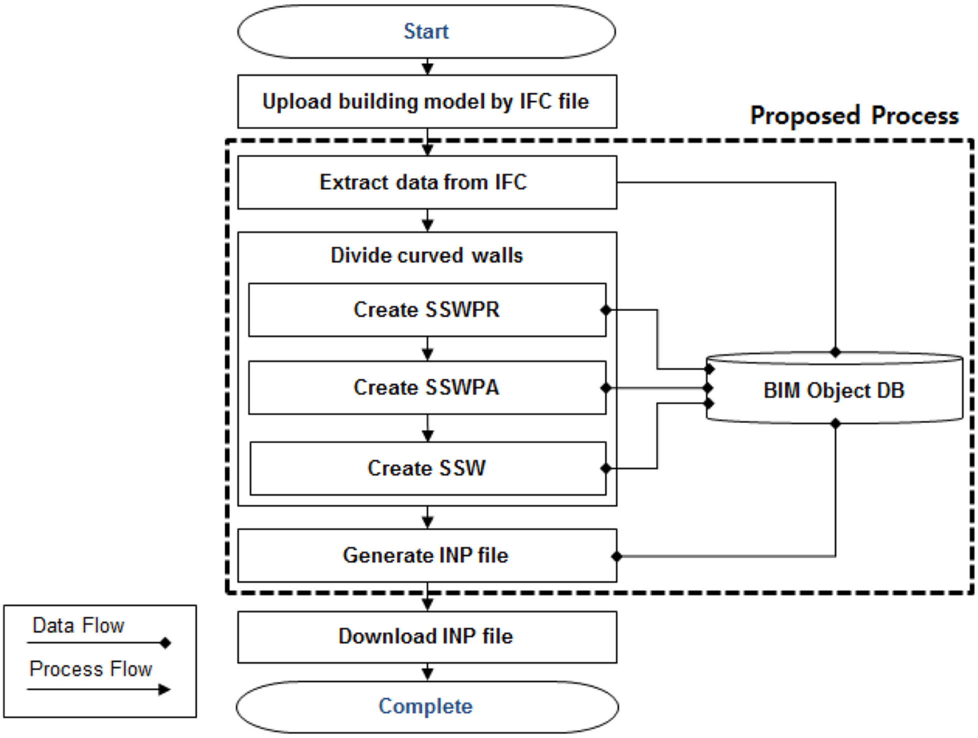

Fig. 3. Overall process

$SSWPA'_n$ must be moved by the function of move as Eqn (10):

$$\text{Function of move } SSWPA'_n = (\text{Location coordinates}) - (SSWPA'_0). \quad (10)$$

Using the function of move, all of the $SSWPA'_n$ are moved to the original location of the curved wall as $SSWPA'_n$.

2.3.3. Process of creating SSW_n

To create SSW_n between $SSWPA_n$ as an element, the distance between $SSWPA_n$ must be known to use the reference line of the created SSW_n. Eqn (11) is used to calculate the distance of $SSWPA_n$ (Fig. 8):

$$\text{Distance} = \sqrt{(X_n - X_{n-1})^2 + (Y_n - Y_{n-1})^2}. \quad (11)$$

2.4. Process of generating INP file

The created SSW_n must have specific attributes, such as the material and the thickness of the original curved wall. To that end, the attribute data are loaded into the created SSW from the BIM object DB. Finally, the created SSW_n, including the attributes of the original curved wall, can be entered into an INP file as a building description of the DOE-2.2 BEA engine. The created placement and representation data of the created SSW_n can be converted to the INP format according to Table 1. According to the DOE-2.2 manual (James J. Hirsch & Associates 2009), the required data of a wall in an INP file is defined by four data. The height data is replaced by the depth data in the extracted data. In addition, the width data is replaced by the length of SSW_n. The coordinates of X, Y, and Z can be filled by the created $SSWPA_n$. Moreover, the required data for the INP file must have the units of ft-lb.

The data format of the INP file can be structured as an exterior wall data template used to generate an INP file. Figure 9 is a template of INP file using the data mapping table. In this regard, the attributes applied to the can be added to the template as property data. For example, a curved wall might contain material information in IFC file. Then, the material information can be applied to the created SSW_n as an additional applied attribute.

The process of generating an INP file, including the attributes of the curved wall, is shown in Figure 10.

3. Verification

To verify the proposed process, a sample curved wall was modeled by ArchiCAD version 14 and named model A. Contrastingly, the curved wall was remodeled with three SSWs by the same CAD program as a practical case of the BEA process and was named model B (Fig. 11). Thus, the verification process shows the difference in terms of the representation data between the proposed process using models A and B. For model A, the value of the curved wall was 113 degrees; however, for model B, the location points of each straight wall have an angle of 38 degrees.

Models A and B were exported to the IFC model using the ArchiCAD 14 translator. Since model A include a curved wall, the representation data can be extracted, as shown in Table 2, by the proposed process (Fig. 12).

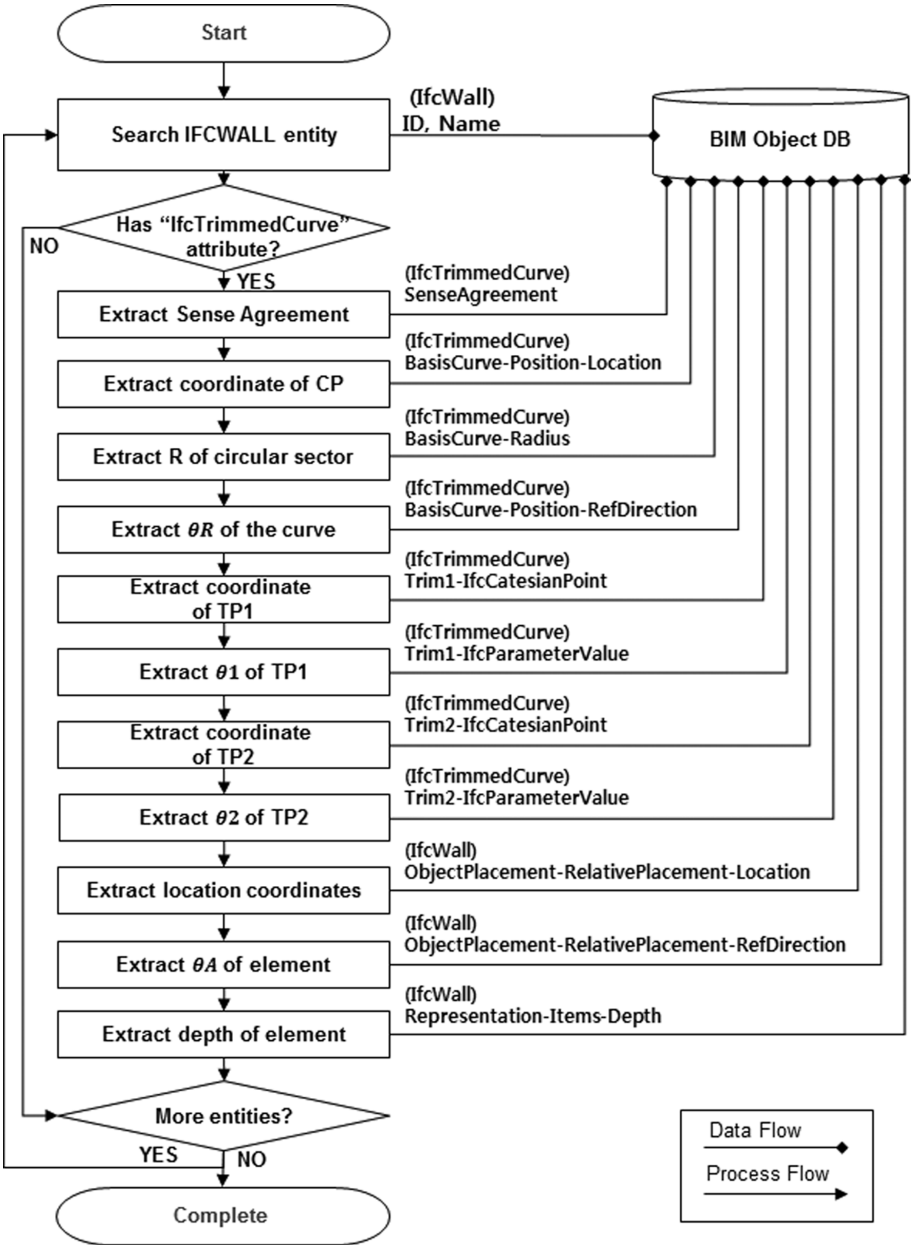

Fig. 4. Process to extract data from IFC

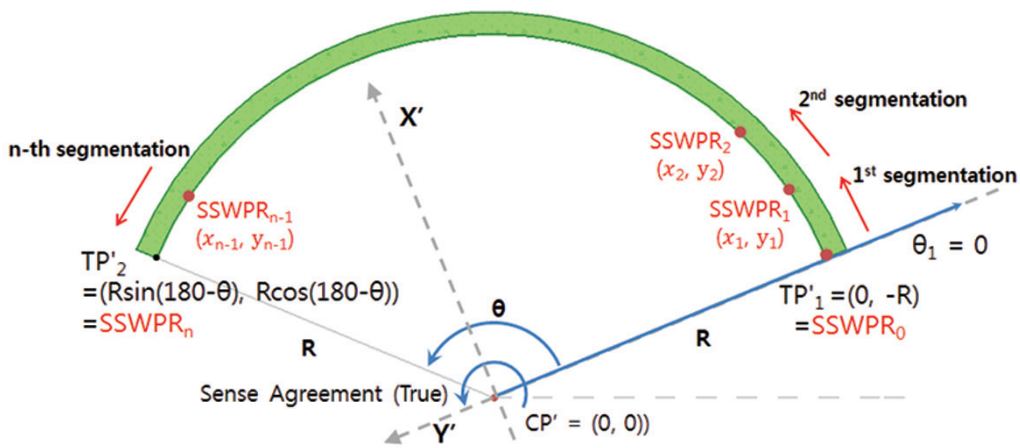

Fig. 5. Concept of rotated $\mathbf{SSWPR_n}$ based on CP'

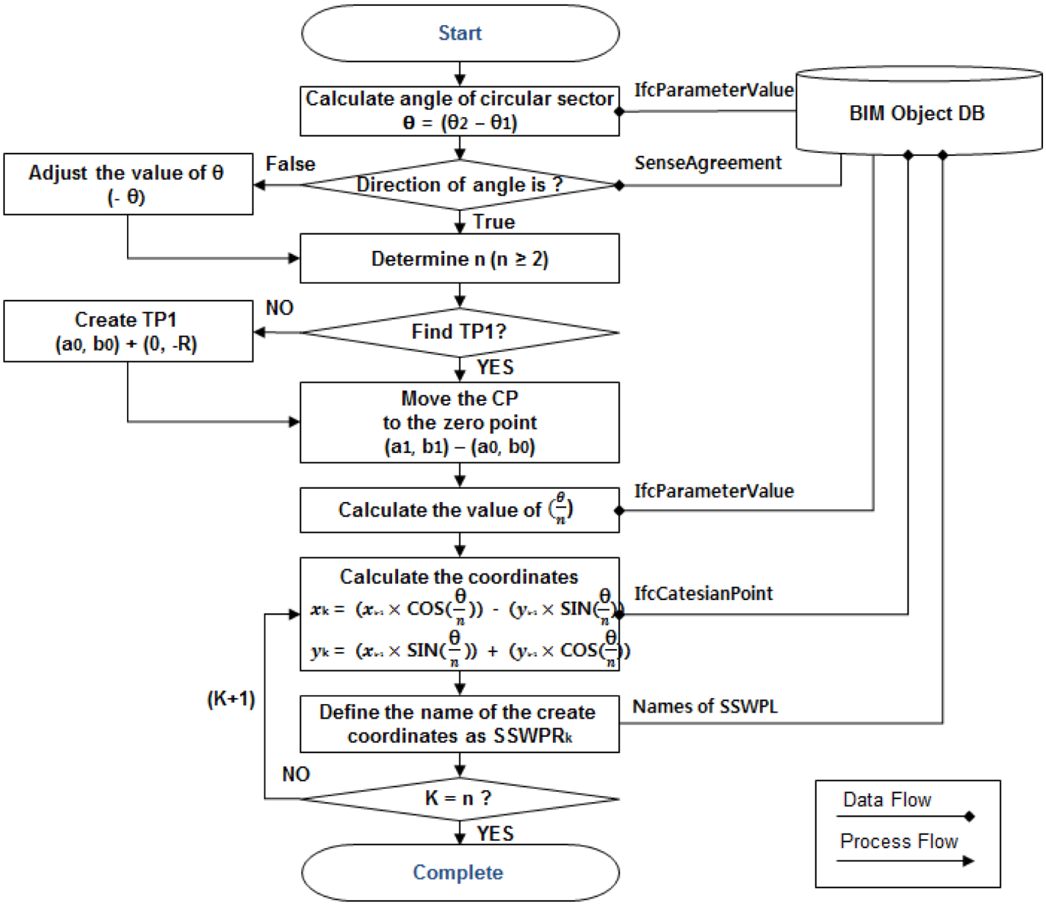

Fig. 6. Process to create **SSWPR**$_{\mathbf{n}}$

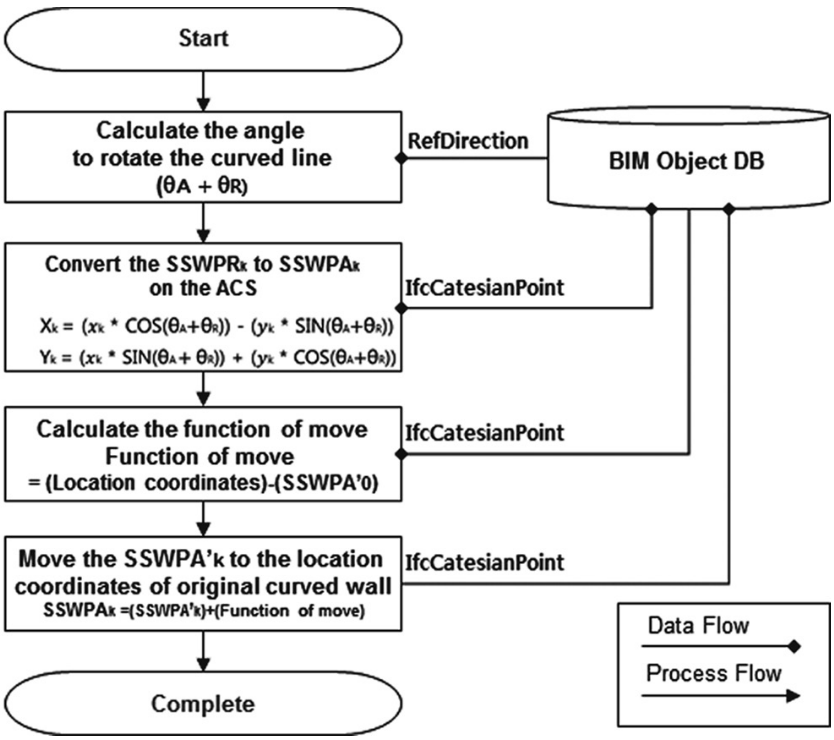

Fig. 7. Process of **SSWPA**$_{\mathbf{n}}$

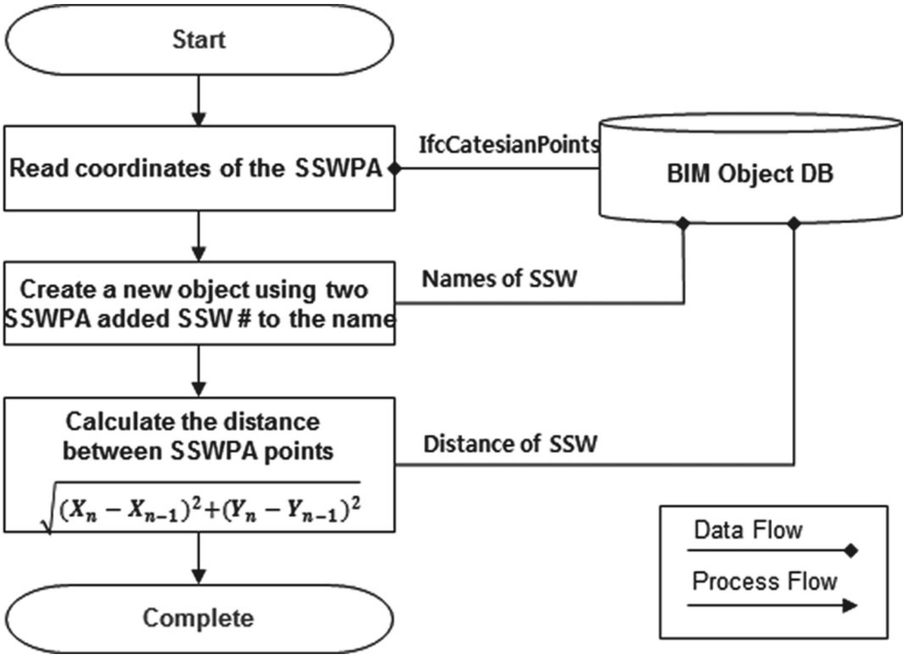

Fig. 8. Process to create $\mathbf{SSW_n}$

Table 1. Data mapping to generate INP file

Required data for INP file	Data from BIM object DB	Description
WALL NAME	Name of SSW_n	The name value of a created SSW_n.
HEIGHT	Depth	The height value of an element.
WIDTH	The length of SSW_n	The width value of an element.
X	The coordinates of $SSWPA_n$	The location coordinates as a start point of an element.
Y		
Z		

“Name of SSW_n” = EXTERIOR-WALL
HEIGHT = “Depth”
WIDTH = “The Length of SSW_n”
X = “Cordinates of X axis”
Y = “Cordinates of Y axis”
Z = “Cordinates of Z axis”
(Additional applied attributes)
..

Fig. 9. Template of INP file

Table 3 shows the location points, i.e., the starting point of each element’s reference line on the ACS, of the straight walls for model B.

Next, the CP is moved to the zero point in the X’-Y’ system to rotate the TP1. TP1 and TP2 also are moved 6,000 mm in the direction of negative Y’. Then, the TP_1' point is rotated basis on CP' to create $SSWPR_n$, as follows:

$SSWPR_1$:

$$x = (0 \times cos(37.628)) - (-6{,}000 \times sin(37.628)) = 3663.232;$$

$$y = (0 \times \sin(37.628)) + (-6{,}000 \times \cos(37.628)) = -4751.919.$$

$SSWPR_2$:

$$x = (3663.2 \times \cos(37.6)) - (-4751.9 \times \sin(37.6)) = 5802.460;$$

$$y = (3663.2 \times \sin(37.6)) + (-4751.9 \times \cos(37.6)) = -1526.919.$$

$SSWPR_3$:

$$x = (5802.4 \times \cos(37.6)) - (-1526.9 \times \sin(37.6)) = 5527.708;$$

$$y = (5802.4 \times \sin(37.6)) + (-1526.9 \times \cos(37.6)) = 2333.333.$$

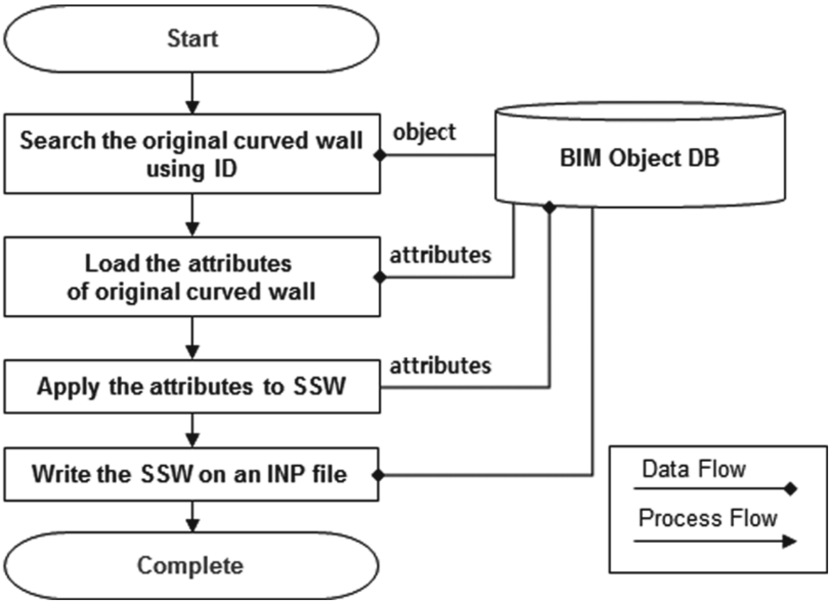

Fig. 10. Process of generating INP file

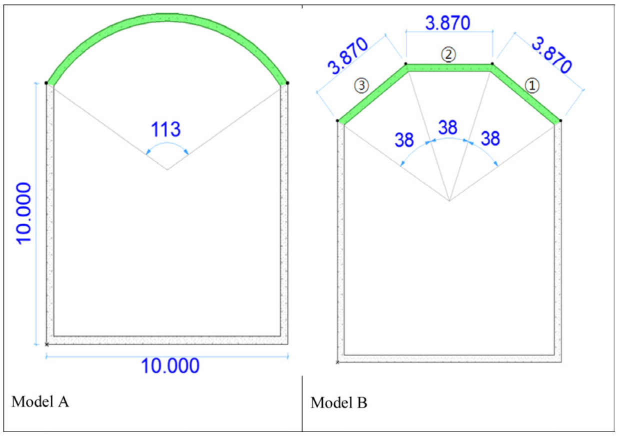

Fig. 11. Sample models

Table 2. Data extracted from model A

Data name	Data value
Center Point	(0, 6000)
Radius(R)	6000
Ref Direction (θR)	90
Ref Direction (θA)	33.56
Sense Agreement	True
Trimmed Point1 (TP1)	(0, 0)
Trimmed Angle1 (θ1)	0
Trimmed Point2 (TP2)	(5527.707984, 8333.333333)
Trimmed Angle2 (θ2)	112.8853805
Location Coordinates	(0, 10000)

Since the created $SSWPR_n$ must be converted to the X-Y system as the ACS, they were rotated by the angle of value rotation (i.e. θA + θR), as follows:

$SSWPA'_0$:

$X = (0 \times \cos(123.56)) - (-6000 \times \sin(123.56)) =$
$4999.844;$

$Y = (0 \times \sin(123.56)) + (-6000 \times \cos(123.56)) =$
$3316.860.$

$SSWPA'_1$:

$X = (3663.2 \times \cos(123.5)) - (-4751.9 \times \sin(123.5)) =$
$1934.738;$

$Y = (3663.2 \times \sin(123.5)) + (-4751.9 \times \cos(123.5)) =$
$5679.506.$

$SSWPA'_2$:

$x = (5802.4 \times \cos(123.5)) - (-1526.9 \times \sin(123.5)) =$
$-1935.271;$

$y = (5802.4 \times \sin(123.5)) + (-1526.9 \times \cos(123.5)) =$
$5679.324.$

$SSWPA'_3$:

$x = (5527.7 \times \cos(123.5)) - (2333.3 \times \sin(123.5)) =$
$-5000.156;$

$y = (5527.7 \times \sin(123.5)) + (2333.3 \times \cos(123.5)) =$
$3316.390.$

The calculated $SSWPA'_n$ must move to the original location of the curved wall in model A. $SSWPA'_n$ were moved as

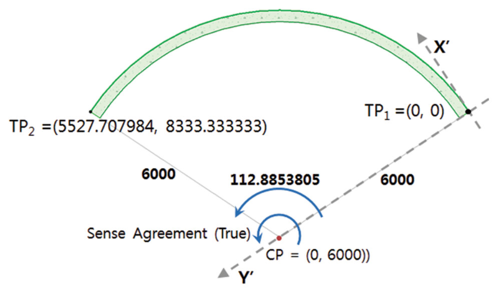

Fig. 12. Points extracted from model A

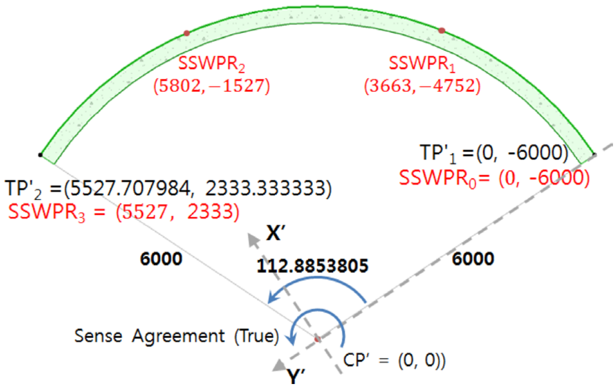

Fig. 13. Created $\mathbf{SSWPR_n}$

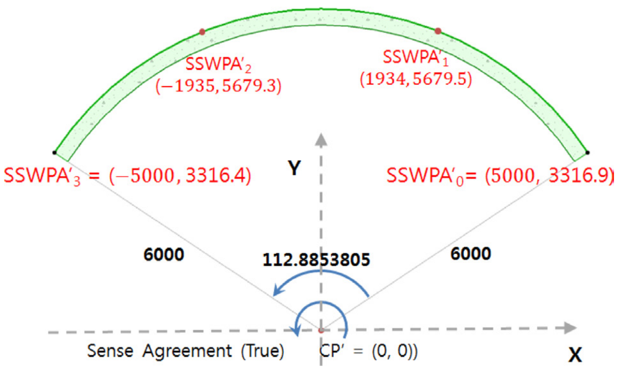

Fig. 14. Created SSWPA'_n

Table 3. Data extracted from model B

Data name	Data value
The location point of element 1	(6935.004779, 12362.79036)
The location point of element 2	(3065.086446, 12362.82144)
The location point of element 3	(0, 10000)

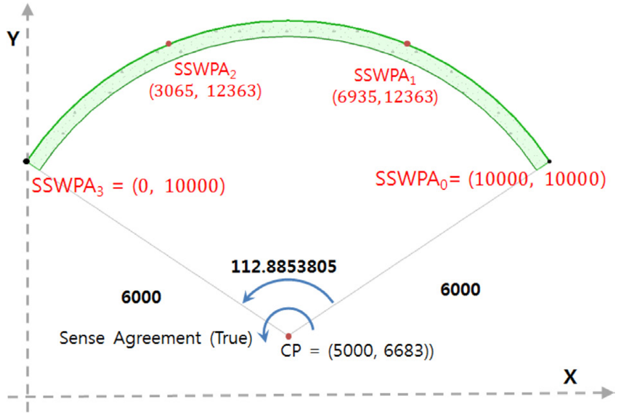

Fig. 15. Created $\mathbf{SSWPA_n}$

Function of move SSWPA'_n (i.e. (0, 10000) – (–5000.156, 3316.390) = (5000.156, 6683.610), as follows:

SSWPA_0 :

$$(4999.844, 3316.860) + (5000.156, 6683.610) = (10000.000, 10000.470).$$

SSWPA_1 :

$$(1934.738, 5679.506) + (5000.156, 6683.610) = (6934.864, 12363.116).$$

SSWPA_2 :

$$(-1935.271, 5679.324) + (5000.156, 6683.610) = (3064.885, 12362.934).$$

SSWPA_3 :

$$(-5000.156, 3316.390) + (5000.156, 6683.610) = (0.000, 10000.000).$$

Using the SSWPA_n, the SSW_ns can be created as model A' (Fig. 16). The length of SSW_n is calculated as follows:

SSW_1 :

$$\sqrt{(10000 - 6934.864)^2 + (10000 - 12363.116)^2} = 3870.319874.$$

SSW_2 :

$$\sqrt{(6934.864 - 3064.885)^2 + (12363.116 - 12362.934)^2} = 3869.979004.$$

SSW_3 :

$$\sqrt{(3064.885 - 0)^2 + (12362.934 - 10000.000)^2} = 3870.009968.$$

According to the previous process, a comparison between the calculated coordinates of SSWPA_n from model A' and the location coordinates from model B are shown in Table 4. As a result, the coordinates of the creat-

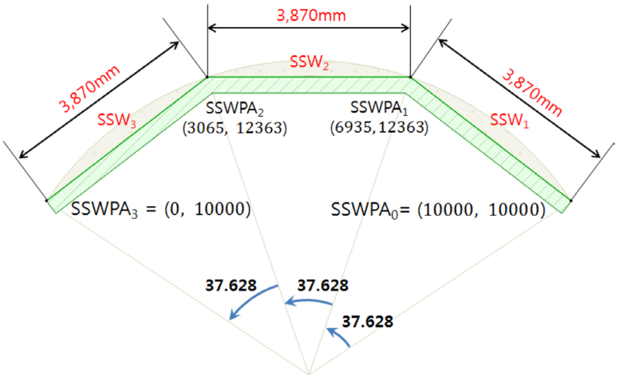

Fig. 16. Representation data of model A' with **SSW_n**

ed $SSWPA_n$ in model A' are the same as the location coordinates of the elements in model B except that they are rounded off to the nearest integer.

Model A' with can be converted to an INP file as a building description for the DOE-2.2 engine. In the INP format, several representation data of a wall are necessary for BEA, such as height, width, and the coordinates of the location (i.e. X, Y, and Z axes) (Kim, Yu 2012). To convert the representation data of model A', the required data must be filled by $SSWPA_n$ and SSW_n using the units of ft-lb. The height data were filled by the attributes of the original curved wall: in this case, the height was 2,800 mm (9.186 ft). The width data were filled by the calculated length of SSWn: in this case, the width was about 3,870 mm (12.7 ft). The coordinates of the location data were filled by $SSWPA_n$ as the value of X and Y axes (Table 5). However, the Z axis was filled by the evaluation of the original curved wall as an attribute: in this case, the evaluation value was zero.

Conclusions

Since BIM technology is systemically being used in the BEA process, BEA engineers can use a 3D-based building model in the BEA process, thereby making simulation of the building's energy usage more accurate and efficient; however, since the current BEA process cannot use representation data and include a curved wall directly, the building model must translate the curved wall into a number of SSWs to recognize the representation data in the BEA program. As this, remodelling work must be done manually, it opens up the opportunity for human error. In addition, since the results of the remodelling work might differ from worker to worker, the accuracy and reliability of the BEA results are reduced. As the number of the SSWs increases, the accuracy and reliability also increase; however, since the remodelling work is manual, the ability to determine the number of SSWs is limited.

Table 4. Comparison between models A and B

$SSWPA_n$	Model A'	The element	Model B
$SSWPA_3$	(0.000, 10000.000)	element 3	(0, 10000)
$SSWPA_2$	(3064.885, 12362.934)	element 2	(3065.086446, 12362.82144)
$SSWPA_1$	(6934.864, 12363.116)	element 1	(6935.004779, 12362.79036)

Table 5. Representation data to convert INP file

Coordinates from Model A	Location points	Element	Coordinates value	INP format (ft-lb units)
CP = (0, 6000) R = 6000 θR = 90 θA = 33.56 Sense Agreement = True TP1 = (0, 0) θ1 = 0 TP2 = (5527.707984,8333.333333) θ2 = 112.8853805 Location Coordinates = (0, 10000)	$SSWPA_3$	SSW_3	(0.000, 10000.000)	SSW3 = EXTERIOR-WALL HEIGHT = 9.19 WIDTH = 12.7 X = 0.0 Y = 10000.0 Z = 0.0
	$SSWPA_2$	SSW_2	(3064.885, 12362.934)	SSW2 = EXTERIOR-WALL HEIGHT = 9.19 WIDTH = 12.7 X = 3064.885 Y = 12362.934 Z = 0.0
	$SSWPA_1$	SSW_1	(6934.864, 12363.116)	SSW1 = EXTERIOR-WALL HEIGHT = 9.19 WIDTH = 12.7 X = 6934.864 Y = 12363.116 Z = 0.0

To solve this problem, we proposed a process to divide curved walls in IFC into segmented straight walls for BEA. To that end, we first, defined the extracted data for the proposed process. Then, a trimmed point was rotated by a specific angle to create the new location coordinates using a trigonometric function. After that, the straight walls were created between the calculated points as a building element. Finally the attributes of the original curved wall were applied to the created SSW_n. To verify the proposed process, two sample models were used to evaluate the proposed process, i.e. model A, which included a curved wall, and model B, which did not. The results indicated that the coordinates of the created $SSWPA_n$ in model A' were almost the same as the location coordinates of the element in model B.

There is a few advantages over the three current approaches, comprised of the following: 1) human-dependent tasks that can easily create mistakes in the BEA process are reduced; 2) data interoperability of a building model is assured by the use of the IFC file format; 3) reliability and consistency of the BEA result are increased; and 4) the BEA process can be more efficient because additional building models only for a BEA purpose (such as gbXML) are no longer necessary.

This process will enable engineers involved in a BEA process to use a BIM-based building model directly in the BEA program without having to do additional work. Consequently, this process can contribute toward ensuring the accuracy and reliability of the results of the BEA. As n of SSW_n increases, the possibility of error in the results of the BEA decreases. In addition, since remodelling a building model for BEA will no longer be necessary, the efficiency and objectivity of the BEA process increases dramatically.

Future work should further evaluate a BIM-based building model as a practical case, including various wall, slab, and roof types. In addition, elliptical and free-form curved walls should be considered with the proposed process.

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