Robot-Oriented Design for Production in the context of Building Information Modeling

F.R. Correa[a]

[a]Escola Politecnica, University of Sao Paulo, Brazil
E-mail: fabiano.correa@usp.br

Abstract –

Construction industry must make more extensively use of automation and robots in order to increase its productivity and reduce its impact in the environment. It seems that the first steps in this direction was taken with the Building Information Modeling (BIM) paradigm. Wide adoption of BIM, particularly for the activities of project and construction planning, could be exploited also in trying to introduce more control to the final processes of building construction through a computer interface, from design to production. The main motivation for this research is to study the impact of BIM in bridging the gap between design and construction. Considering the growing interest in applying additive manufacturing technology for future building construction, this paper proposes a computer-aided system that translates a generic architectural project in a set of pieces to be fabricated with 3D printers. The system uses a proposed set of algorithms to process the architectural project: it considers the division of the building in different parts or pieces to be fabricated, based on the work volume of the printer; it also considers the relative position of the part in the bed of the printer, for best results in production; minimum dimension of features to achieve mechanical resistance; and geometric features that would demand support material. IFC standard, in its fourth version, was analyzed for validation in the process to carry all the relevant information produced in design phases to fabrication.

Keywords –

BIM Integration with Robotics; IFC; Additive Manufacture

1 Introduction

Few countries could be regarded as *avant-garde* in the use of automation and robots by the construction industry [1]. In a global perspective, it turns out that the construction industry, albeit its relative importance in the economy of each country is still behind other industries in terms of adopting new technologies to increase its productivity and reduce its impact in the environment. Moreover, this scenario is critical in developing countries like Brazil, which have under qualified and cheap labor, turning more difficult the introduction of costly solutions, even when producing better products.

There are many reasons for this situation, and the cost of implementation is one of them. In that regard, there is a range of technologies that could be exploited by the construction industry, in which the costs varies a lot. One extreme being the use or the investment in research for the use of robots for off-site or on-site pre-fabrication, and on-site assembly.

The other extreme are software developments and IT technologies promoting the automation of many of the common processes, which today are under the Building Information Modeling (BIM) paradigm [2].

Nevertheless, there is a discontinuity between implementations using each of the two extremes, mostly because 3D CAD is still used in some countries in applications that could be solved with BIM technology [3]. Consequently, there is a missed opportunity to capitalize in the integration of both extremes, as occurs in other industries with CAD/CAE/CAM (Computer-Aided Design/Engineering/Manufacturing) approaches.

However, the increasing rate of adoption of BIM, particularly for the activities of project and construction planning, could be exploited also in trying to introduce more control to the final processes of building construction through a computer interface, from design to production. Ultimately, the production could be done by CNC machines and industrial robots [4].

The main motivation for this research is to study the impact of BIM in bridging the gap between design and fabrication, in a future scenario where different robots could be used on-site, for example, for the final assembly of pre-fabricated modules.

To achieve that goal, the focus in this article is in how a computer-assisted design software could make the design process transparent to the architect for production based on a 3D printer. Following the concept of Robot-Oriented Design (ROD) [5], the system will automatically introduces features and changes in the final geometry to be able to produce a functional building that could be 3D printed. The proposed system considers:

- Division of the building in different parts or pieces to be fabricated, based on the work volume of the printer;
- Relative position of the part in the bed of the printer, for best results in production;
- Minimum dimension of features to achieve mechanical resistance;
- Geometric features that would demand support material.

In this case, the integration from design to production or between BIM and Robotics is achieved with the use of the IFC Schema to represent BIM model with building design, and the transformation of that information in an STL file to be used in a 3D printer.

The IFC file format is the de facto standard in the construction industry and the way information is passed between different professionals and software platforms. IFC standard, in its fourth version, was analyzed for validation of the process to carry all the relevant information produced in design phases to fabrication.

It is also discussed the role that additive manufacturing could have in this scenario, when multi-material and control of mechanical properties along different parts of the same component become commonplace.

2 BIM Integration with Robotics

Although BIM has been largely adopted by many countries, and is the responsible for inserting new computational technologies in AEC, it did not bring along direct opportunities for automation and / or the use of robots in construction. In part, this observation is because most BIM implementations are for project or planning, and not for fabrication / construction [6].

BIM could be associated with the CAD / CAM / CAE in mechanical engineering, but the percentage of use of CAM is very limited. There are a few examples in using BIM for fabrication or production, mostly in Japan and China [3].

The interest of manufactures in participate in BIM processes could be viewed in two different scenarios [7]:

1. Producing models/components which represents its products in detail and could be directly used inside BIM models in design or construction;
2. To fully extract rich details of the models and use the information to fabricate certain components, as steel components for HVAC.

For the discussion presented in this article, the focus will be in the second reason.

In working with a 3D printer to fabricate components of an architectural design, the main reason is to collaborate in proposing solutions and identify difficulties in the path for integration of BIM with Robotics.

All the construction information are contained in IFC files, the open BIM standard.

2.1 IFC

In studying the impact of BIM for production, it is important to deal with Industry Foundation Classes (IFC) standard [8]. It is a standard that evolved for almost two decades, and since 2013, is ISO 16739 standard.

IFC was conceived to accommodate construction information regarding all lifecycle of a building.

The main interest in dealing with IFC is to locate all the necessary information to process and analyze each component of the model, and eventually to store information for production inside the model. As an open standard, the solution could be easily ported in a proprietary BIM model.

Although IFC is not the primary file type in authoring BIM tools, it is part of the process when the model needs to exchange information between different applications. So, in the case of fabrication or production, it is necessary to explore if IFC could contain properly all the information necessary to fabrication, information which is used by computer controlled machines and robots. In the case of this article, it would be explored if IFC files could represent STL format which is used in 3D printers.

The main interest in IFC for this particular work regards how the components of an architectural project design could be geometrically represented inside IFC.

2.1.1 Geometric Representation

IFC schema allows the representation of building elements in many different formats. Two are of particular interest:

- Boundary representation: to simplify the approach, it will be used only the *IfcFacetedBrep* (Figure 1) representation instead of the more free-form allowed with *IfcAdvancedBrep*;
- Tessellated: this representation would be valuable to communication with 3D printer and translation to STL format. It uses the *IfcTriangulatedFaceSet* (Figure 2).

In boundary representation, all vertex of the solid are in the end represented as *IfcCartesianPoint*. The triangulated representation could be created directly from the solid resultant from the alterations proposed by the system.

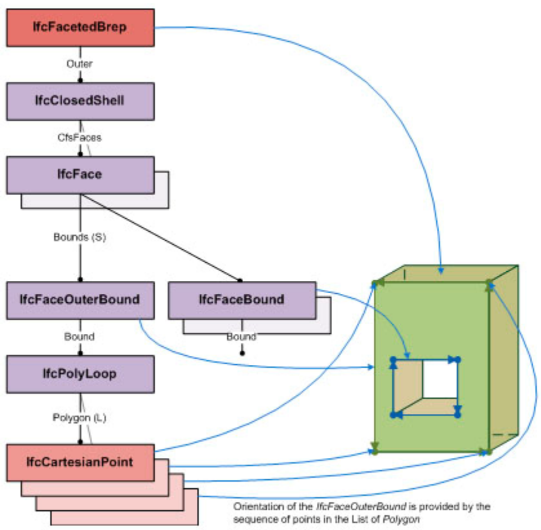

Figure 1. Entities of the IFC schema used to represent a building component with Brep representation [8].

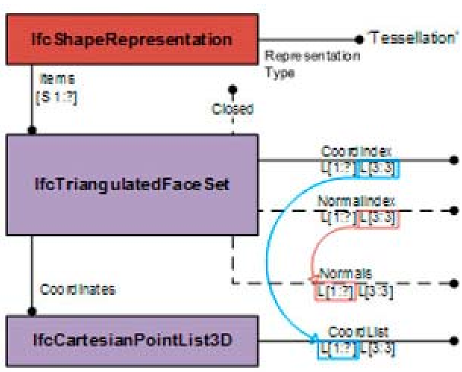

Figure 2. One of three forms of specify a component with *IfcTriangulatedFaceSet* [8].

2.2 Additive Manufacturing in Construction

Additive manufacturing, more popularly known as 3D printing, has been considered a disruptive technology in regarding manufacture processes [9]. It already was successfully applied in the automotive, aviation, and health fields.

The process consists of depositing layer after layer of a material that flows through a channel. In addition, this probe could be placed anywhere in the horizontal plane to draw the intended shape. The material must be hard enough to hold its form before receive another layer of material.

In the last years, it has been used for construction, to build parts of a house or building [10][11].

Independent of the technological barriers that still exists, there is not a single vision in the way this process could be applied to construction. Potential exists to avoid material waste, to use recycled material or in situ material, to control the material properties locally, to produce parts with geometric, and so on.

The benefits of this manufacturing process is the freedom of form, its reduced setup time between different components, its potential capacity of work with different materials. Its negative features is the time to manufacture.

With regard to the constraints applicable to production with additive manufacturing, it could be divided in two different categories: geometry in design, parameters of production.

The parameters of production do not affect the geometry of the component but its mechanical properties. For example, the density of the core of the component could be changed based on the final mechanical resistance necessary for that component.

Using BIM for fabrication and trying to promote the additive manufacturing technology for future building construction and interpreted as a robot, this paper proposes a computer-aided system that translates a generic architectural project in a set of pieces to be fabricated with 3D printers.

3 CAM for Additive Manufacturing

CAM is used in many industries for a long time, existing for the majority of the production system. However, additive manufacturing is a relative novel process that is still under continuously development, primarily because new materials are been conceived to better exploit its potentiality [9].

Some computerized systems exists that deal with Additive Manufacturing [12], but the difference is that it helps in the design process, and the proposed system try to correct the design without the input of the user. Other systems are similar in trying to create a geometry-based grammar to interpret the design [13].

The proposed system consists of a software that processes a BIM model, and extract from it a batch of components to be 3D printed. Normally, the designer of mechanical parts must have a very well understanding of the fabrication process involved in manufacturing the part designed by him. In such scenario inside the construction industry, one architect could design a façade, and send it directly to a CNC controlled machine or a robot for fabrication.

In developing such system, three questions had been considered:

- To create an abstraction between design and production based on additive manufacturing, so that the architect could concentrate in its intents;
- To promote the entrance of the additive manufacturing in the construction industry;
- To work with the principles of ROD, in which it helps the construction industry to perceive the added value brought by automation and robotics.

For the following discussion, it will be considered that the 3D printer possesses only one head of extrusion, and thus works with a single material, PLA. Unfortunately, it would be difficult to make all the discussions necessary here in using a material appropriate for the construction industry, such as concrete, which is still matter of intensive research. However, the discussion provided and results obtained are still valid for other materials.

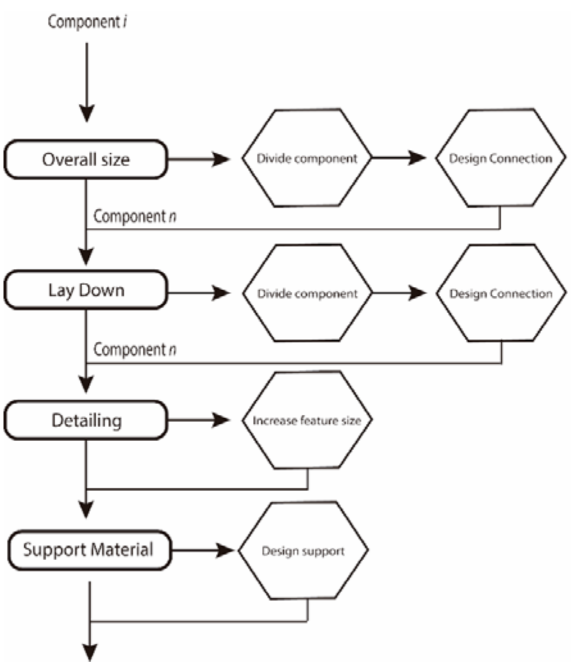

Figure 3. Diagram of the analysis flow for each component of the BIM model.

The methodology of the presented research consists in: 1) Enumerate geometric characteristics or features in building components that would be difficult or impossible to achieve with a standard FDM 3D printer using PLA; 2) To propose a workflow where these features would be automatically and entirely detected in processing a BIM file; 3) Implement algorithms to slightly change those features in each component, so that it could be printed; 4) Print the entire project with the eventually altered parts, and contrast it with initial design intent;

The main objective in developing such system is to study if the designer, i.e. the architect, could have a larger liberty in the design process, relaying some decisions to an expert system, which will most fatefully translate its intent to produce components through 3D printing.

In the following sections, it will be discussed all the characteristics of components that the proposed system verifies. For each component of the model, the analysis workflow is depicted in Figure 3.

Each step verify a specific characteristic (in the diagram, round boxes indicates that a verification occurs). If it passes in the verification, it go for the next step. If not, it is directed to pass through some functions, which could alter the geometry of the component. In some cases, it could create new components from the original one (in the diagram, each hexagon represents an operation on the geometry of the component, altering thus the original geometry of the architect, but not, hopefully its intent).

All the geometric reasoning is based on a voxel representation of the components (Figure 4). It could be implemented using efficient data structures such as octrees, but in this case, as each component have a relative small size, the gains are negligible.

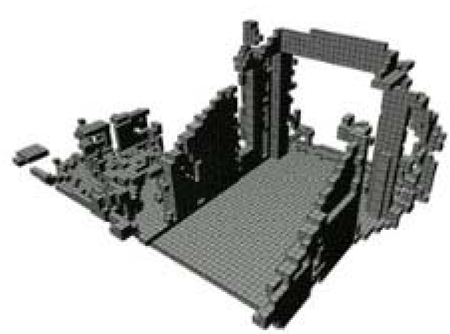

Figure 4. An example of how architectural components could be represented with octrees [14].

The transformation algorithm starts by transforming each building component in a discrete representation composed of voxels. The size of each voxel is chosen to be equal to the diameter of the 3D printer.

Each voxel receives one of three possible values: { 0, 0.5, 1 }. If the voxel is entirely filled by the component, it receives 1; if it is completely empty, 0; and 0.5 when there are voids inside the voxel. Thus, the representation works by indicating when a specific feature of the component is too detailed as to be 3D printed.

Processing the information on the voxel, it is possible to do all the verification necessary for the proposed system. In addition, it enables the discrete localization in each component for insertion of additional features, such as connectors, and to cut for division of a large component.

All considerations regarding proper design for 3D printing was based on [15] and the own experience of the author. In the following sections, an overview of the workflow is presented, along discussion on how the information generated is stored in IFC files.

3.1 Overall Size

In checking if a component could be printed in one piece, it must not be larger than the workspace of the printer. The bounded box that contains the piece is used in that verification.

In IFC Schema, the entity *IfcBoundingBox* and its attributes *Corner* (*IfcCartesianPoint*), *XDim*, *YDim*, and *ZDim* (*IfcPositiveLengthMeasure*), and *Dim* = 3 (*IfcDimensionCount*) must be filled accordingly.

The volume of the workspace is defined as the size of the bed multiplied by the useful height of the printer. The volume of the bounding box must be smaller than that value:

$$IfcBoundingBox.XDim * IfcBoundingBox.YDim * IfcBoundingBox.ZDim < Workspace\ Volume \quad (1)$$

If the size is larger, it must be divided in more than one part, and certain features will be created which would warrants a consistent assembly. This division must produce as few pieces as necessary to print. If more than two parts are necessary, it must produce parts with similar size. The location of the division is based on the voxel discretization of the component.

It would be interesting to create a library of possible connections; the system implements the connector depicted in Figure 5. Its size must be compatible with the size of the voxel

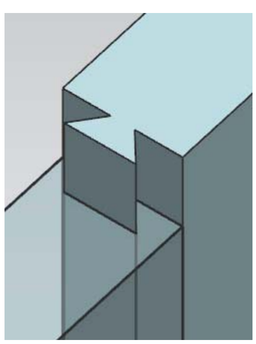

Figure 5. One example of possible parametric connections between components.

3.2 Position in Bed

Checking for best position in laying it out in the printer bed, could avoid the use of support material, shrinkage effects and promote best adhesion . The system searches for the face that have the larger area in the piece. It uses the voxel representation trying to find an external layer that is completely filled.

The final position of each component will be stored on the entity *IfcLocalPlacement*, relative to the coordinates of the printer's bed, of the entity *IfcBuildingElemenProxy*. It is necessary to create a copy of the original component.

If there is not an entirely flat face to position in bed, the system would try to reap off some features or divide the component in different parts to faces entirely in a plane. As occurs with the first analysis, if the component is split in parts, connections would be added to realize the posterior assembly.

The algorithm needed to produce the division in the component to be adequately positioned in bed is different from the algorithm of overall size.

3.3 Detailing

If the component has some fine detailing, it is necessary to known the diameter of the extrusion nozzle, because the printer cannot obtain a detail that is smaller than that parameter.

The algorithm to find and analyse the details of the components must first identify each detail and isolates it. This occurs when the component is transformed in the voxel representation, and could be determined by aggregating neighbouring voxels in the same layer.

3.4 Support Material

Although it must be avoided, to produce certain components directly instead of assembling different components in a final shape, it could be necessary to produce a support material to give shape to the component. Actually, the system do not implement an algorithm to customize the support material, relying instead in the own printer software to do that.

The verification must search for two different type of features: overhang (Figure 6) and bridging (Figure 7), based on the positioning of the component in bed.

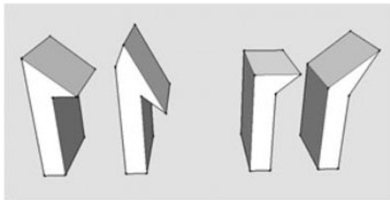

Figure 6. Examples of overhangs: only the two on the right will print correctly without support material [15].

If there are overhangs, and if the inclination of the face is more than 45 degrees from the vertical, it will need support material. If the angle is about 60 degrees, it could be printed but it will be necessary to use the cooler.

Bridging would demand the division of the component in the exact position the that feature.

The support material would be represented inside IFC Schema by creating an *IfcBuildingElementProxy* with attribute *ObjectType* USERDEFINED and attributing to it a geometric representation based on faces.

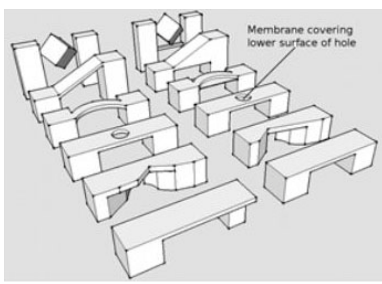

Figure 7. Models in the left will print poorly [15].

3.5 STL Files from IFC

The final step, not depicted in the workflow, would be to generate an STL file for each component. The IFC Schema allows a large number of different geometric representation of the solid. With IFC4, a new form of geometric representation was conceived consisting in transform or in some cases, approximated the geometry of the face of the object using sets of triangles.

For STL format, it is necessary to use the entity *IfcTriangulatedFaceSet* and its attributes *CoordIndex*, *NormalIndex*, and *NumberOfTriangles* = SizeOf(*CoordIndex*).

4 Experiments and Results

The system was implemented using *IfcOpenShell* to parse directly IFC files and written in C++. As *IfcOpenShell* uses *OpenCASCADE* to generate and deal with geometric representation, the voxel representation uses also data structures from *OpenCASCADE*.

Based on a Prusa 3D printer, the configuration parameter for the system are shown in Table 1.

Nozzle diameter affects directly the quality and precision of the final product. No feature with smaller dimension than the nozzle diameter could be produced. Layer's thickness also influences on the final quality of the component and in the time to finish the printing process. The size of the workspace or bed restricts the size of the component to be printed.

Table 1. 3D printer's parameters.

3D Printer's Parameters	Values
Nozzle diameter	0.4 mm
Bed width	20.0 cm
Workspace Height	19.0 cm
Thickness of the layer	0.4 mm
Bed depth	20.0 cm
Diameter of the filament	3.0 mm

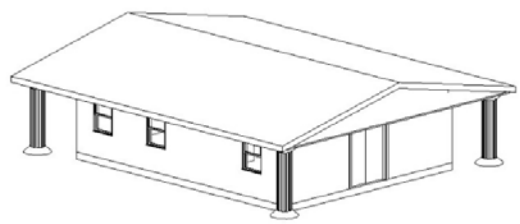

Figure 8. IFC Model.

Figure 9. Component to be tested against support material (bridging).

The model used in the experiment is depicted in Figure 8. It will be printed in a 1:200 scale. It generated 11 different components to be analysed, transformed and printed (windows and doors were not considered in this test). The model was generated in Autodesk Revit software and further exported in IFC format, with the built-in exporter, and was given as input to the system.

In the sequence, some components of this building are highlighted to shown the performance of the system in analysing the design for 3D printing.

Figure 9 illustrate one external wall of the house, which because of the main entrance, present the problem of bridging when printed. All walls that have openings (for doors or windows) will present the same problem.

The result of the analysis and transformation of the component generated by the system is illustrated in Figure 10. It shows the division of the wall in three pieces because of its size of 41 cm, and the inclusion of features to connect the different parts.

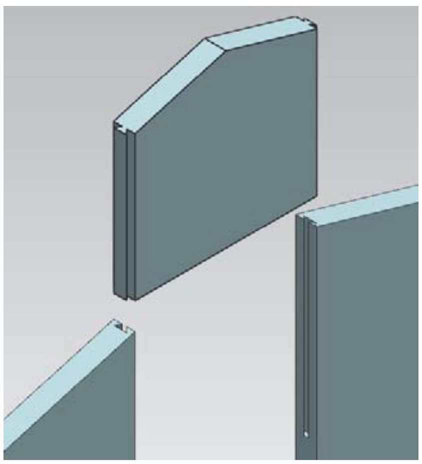

Figure 10. Result from algorithm divide.

In other type of analysis, Figure 11 represents an interior wall whose position in bed for printing is a challenge, without resorting to support material, when considering a larger surface of bed adhesion.

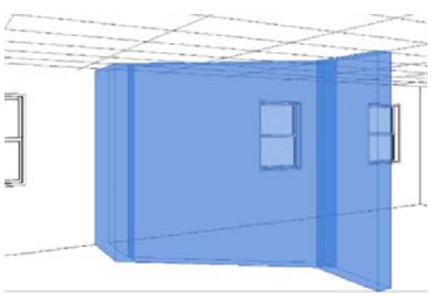

Figure 11. Wall with singular geometry to be tested against lay out position.

As the implementation do not considers a trade-off between size of the area in bed and the necessity of support material or to divide the component (which is not trivial), it instead adopts some priority verification. Thus, the final position to be printed is as depicted in the figure to avoid support material, although this position generate a small area of adhesion.

Based on the voxel representation and the constraint of the size of the nozzle, the depth of all walls were changed from 1 mm to 1.2 mm to accommodate it.

The most difficult operation to realize automatically is to change the feature detailing that could not be printed adequately because of its size. Eliminating such detail is not a solution when the intention of the architect is lost.

Figure 12 illustrate a column with some fine detail that could not be printed as it is. Figure 13 and Figure 14 shows how it was modelled and it is through this analysis that the system could change the number of repetitions along the circle, the size of each detail, and so on.

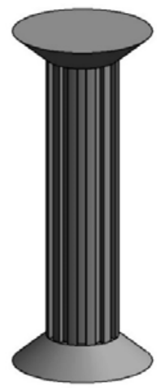

Figure 12. Column with parametric feature.

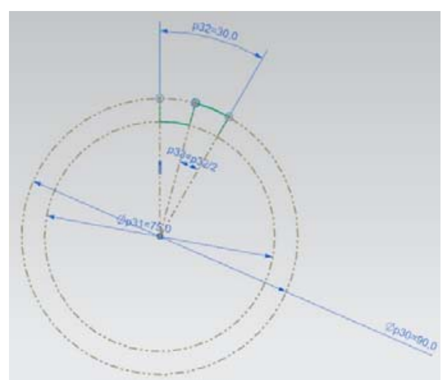

Figure 13. Parametric feature capturing design intent.

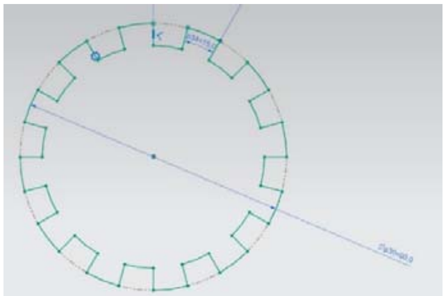

Figure 14. Pattern Curve to create the parametric profile.

To solve this problem some sort of parametric analysis must be provided, but it was not implemented in the current version of the system. However, the IFC Schema in its fourth version could represent such parametric features and models.

5 Conclusion

The initial development of a system that interprets architect's design intent and translate it in a batch of components to be 3D printed was presented. The context in which such system could be useful is in the integration of BIM and robotics.

It was shown the results produced by the system under construction for a BIM model of a house. The IFC file format was used to translate the results of the system's interpretation in the process to transform the initial model attending restrictions and constraints of the proposed fabrication process, i.e. additive manufacture.

It seems that the architect could design its building without worrying too much about the restriction presented by additive manufacturing.

As future work directions, it would be interesting to study how this system could be applied in buildings with geometries very particular, of the kind that could uses all the potential of 3D printers. It certainly would demand the use of a feature-based geometry grammar to deal with the reasoning process by the system [16].

References

[1] Bock T. and Linner T. *Robotic industrialization*. Cambridge University Press, New York, USA, 2015.

[2] Eastman C., Teicholz P., Sacks R., Liston K. *BIM handbook – a guide to Building Information Modeling for owners, managers, designers, engineers, and contractors*. John Wiley & Sons, New Jersey, USA, 2011.

[3] Yamazaki Y., Tabuchi T., Kataoka M., Shimaki D. BIM applications to large-scale complex building projects in Japan. In *International Journal of High-Rise Buildings*, 3(4), 311-323, 2014.

[4] Halabi M. The Sagrada Familia: the starting point of CAD/CAM in architecture. *Scientific Cooperations Journal of Civil Engineerning and Architecture*, 1(2), 12-20, 2016.

[5] Bock T. and Linner T. *Robot-oriented design*. Cambridge University Press, New York, USA, 2015.

[6] McGrawHill Construction. The business value of BIM for construction in major global markets: how contractors around the world are driving innovation with Building Information Modeling. Technical Report, 2014.

[7] Bachmann K. How will BIM benefit product manufactures? On-line: https://www.quora.com/How-will-BIM-benefit-product-manufacturers, Accessed: 14/03/2016.

[8] buildingSMART. IFC4-addendum 1 [final standard]. On-line: http://www.buildingsmart-tech.org/ifc/IFC4/Add1/html/, Acessed: 24/03/2016.

[9] CAMM. Strategic roadmap for the next generation of additive manufacturing materials. Technical Report, PennState University, 2016.

[10] Khoshnevis, B. Automated Construction by Contour Crafting—related robotics and information technologies. *Automation in Construction*, 13 (1): 5–19, 2004.

[11] Kreiger M., MacAllister B., Wilhoit J., Case M. The current state of 3D printing for use in construction. In *Proceedings of the Conference on Autonomous and Robotic Construction of Infrastructure*, pages 149-158, Iowa, United States, 2015.

[12] Rosen D. Multi-scale computer-aided design for additive manufacturing. In *Proceedings of the Intenational Conference on Innovative Design and Manufacturing*, Montreal, Canada, 2014.

[13] Ostrosi E.; Ferney M. A grammar based approach for feature modelling in CAD. *Design computing and cognition*, Springer Netherlands, p. 377-396, 2004

[14] Hornung A., Wurm K., Bennewitz M., Stachniss C., Burgard W. OctoMap: an efficient probabilistic 3D mapping framework based on octrees. *Autonomous Robot*, 34: 189-206, 2013.

[15] Smyth, C. *Functional design for 3D printing – designing 3D printed things for everyday use.* CreateSpace Independent Publishing Platform, 2nd edition, 2015.

[16] Fu Z. and Pennington A. Geometric reasoning based on graph grammar parsing. *Journal of Mechanical Design*, 116(3), 763-769, 1994.