Singh, MM, Sawhney, A and Borrmann, A

Integrating rules of modular coordination to improve model authoring in BIM

Integrating Rules of Modular Coordination to Improve Model Authoring in BIM

Manav Mahan Singh[a], Anil Sawhney[b*], and André Borrmann[c]

[a] *Central Public Works Department, Government of India*

[b] *Department of the Built Environment, Liverpool John Moores University, Liverpool, UK*

[c] *Department of Civil, Geo and Environmental Engineering, Technical University, Munich, Germany*

* Department of the Built Environment, Liverpool John Moores University, 3.04 Peter Jost Enterprise Centre, Byrom Street, Liverpool L3 3AF, UK, Email: a.sawhney@ljmu.ac.uk; Phone +44 151 231 2842

Integrating Rules of Modular Coordination to Improve Model Authoring in BIM

As the adoption of Building Information Modelling (BIM) becomes pervasive and its level of application matures, the need to incorporate domain-specific knowledge in BIM authoring tools is also increasing. Rule-based scripts that assist and guide the modeller in model authoring are needed to enhance the level of usage of BIM. The authors developed a framework for incorporation of rule-driven domain knowledge into BIM authoring tools. With the objective of customising the modelling process using a set of rules, the approach presented in this paper combines rules of modular coordination in prefabricated building with BIM. Modular coordination, a dimensional coordination system for sizing and placing building elements within a three-dimensional (3D) reference system, is translated into rules that are incorporated into the BIM authoring tool through object-level and process-level interventions. The study explores various possibilities and options of parametric modelling for integration of identified modular coordination rules in BIM authoring tools. The aim of integrating modular coordination rules is to assist the user during the modelling process. The proposed approach has the potential of reducing inconsistencies and time spent in modelling and documentation allowing the designer to spend more effort on value-adding design tasks. With the help of a case study and an experiment, capabilities of the proposed framework are demonstrated and validated.

Keywords: BIM; modular coordination; knowledge-based BIM; object level development; process level development.

1 Introduction

The design of built environment assets is an information intensive, iterative (Choo, Hammond, Tommelein, Austin, & Ballard, 2004), evolutionary and complex process (Sawhney & Maheswari, 2013). Building design, consisting of architectural and engineering design, has been described as “handcraft”, as it requires “manual expression” of designer’s expertise (Eastman, Sacks, & Lee, 2004). The design process has innovative and creative components requiring the designer to use problem defining, problem-solving, solution finding and decision making skills while experimenting with shape and geometry to meet the project brief. Alongside this, designers and engineers are also involved in production related tasks such as data processing, information retrieval and sharing, document generation, and design coordination. In the traditional two-dimensional (2D) project delivery process, the designer and the engineer expend significant effort in low-value adding production tasks such as drafting and documentation (Sawhney, 2014). Inefficiencies caused by 2D-based approach are now well documented and well understood. A minor change in design invokes either updating all drawings to avoid inconsistencies or lack of coordination in the drawings itself (Monteiro & Poças Martins, 2013). Traditionally, 2D drawings have been the only way of information exchange among the project team members and the coordination among the participants to convey the correct and complete information depends largely on the expertise of the designers (Hergunsel, 2011).

With the large-scale proliferation of BIM in the industry, there is a shift in the distribution of effort between expertise driven tasks and production-oriented tasks (Sawhney, 2014). Due to its model-centric and object-oriented core (Borrmann & Rank, 2010), BIM by its very nature reduces the efforts to be expended by the designer on low value adding tasks. This allows the design team to increase their input to modelling, analysis and other value-generating tasks as the effort needed for production related tasks is significantly reduced in BIM authoring tool itself.

Can BIM authoring environments be further enhanced with domain specific information and knowledge to assist the designer in enhancing value-creation in the design process? The authors conducted this research to answer this question with a case-study to demonstrate the approach that domain-specific knowledge can be embedded in BIM authoring tools to assist the modeller in not only modelling process but for downstream activities such as documentation, visualisation, quantity take-off and information sharing also. Utilising the concept of knowledge-based BIM authoring tools in conjunction with modular coordination, this paper demonstrates the “computer as an agent” construct. In the computer as an agent construct, the computer is thought of as an agent that guides the design process in contrast to the “computer as a draughtsman” or “computer as an oracle” worldview (Lawson, 2005). While the previous body of research has identified the importance and advantages of using BIM and modular coordination, this paper is focused on explaining how modular coordination rules can be integrated into BIM authoring tools to facilitate the overall modular design process in BIM.

2 Context Setting—BIM and Modular Coordination

BIM authoring environments are specialised systems used for the process of generating building information that can be stored, exchanged and shared for several tasks. Modular coordination is a dimensional coordination system used for sizing and placing building elements within a 3D reference system (Indian Standards Institution, 1983a; International Organization for Standardization, 1984). The use of BIM process through the design phase can enhance the value of built environment by allowing designers to take informed decisions at early stages of design (McGraw-Hill Construction, 2014), while modular coordination increases cooperation among stakeholders of building design and construction industry via dimensional coordination. Both the tools, modular coordination and BIM have the potential to improve the design process by enhancing coordination among the project participants (Lu & Korman, 2010; Romcy, Cardoso, Bertini, & André, 2012). BIM has been used to automate and reduce redundant activities such as visualisation, documentation, quantity extraction, and information exchange. However, the effective use of BIM can only be realised when high-quality models are developed that contain the right information at the right level of detail (Ding, Zhou, & Akinci, 2014).

This study explores various possibilities and options to develop rule-based smart building objects for integration of domain-specific knowledge (such as modular coordination rules) with BIM using its parametric modelling capabilities. The building objects should be rule-based smart building objects as they must be customizable under modular coordination rules only, adapt to changes made to the model and interact with other building objects. The aim of integrating modular coordination rules is not limited to assist the designers during the modelling process only but to enhance several other activities in the design process also. It has the potential to substantially reduce inconsistencies and time spent in modelling. Using this as a basis, the authors demonstrate the mechanism for integrating domain-specific rules within the BIM authoring tools to enhance the modelling process.

3 Literature Review

Modular coordination has been developed as a standardisation system where 3D integer lattice acts as a reference frame and a module acts as the unit (March, 2003). It has been widely used as dimensional coordination system for prefabricating building components and industrialised production (McGraw Hill Construction, 2011). With advancement in construction methodology and equipment, the construction process is slowly shifting towards prefabrication techniques to reduce and optimise on-site operations, potentially reducing the time and cost required for delivering a facility. The prefabrication industry is propagating modularization of building components to promote interchangeability of components, reduce on-site waste and optimise a number of available sizes of a particular component, which in turn increases the construction quality also (Chiang, Hon-Wan Chan, & Ka-Leung Lok, 2006).

As identified by the National Research Council, BIM, modular coordination, offsite prefabrication of elements and prefabricated construction system are enabling ideas, concepts, processes and practices impacting the US construction industry significantly (The Modular Building Institute, 2010). BIM process also promotes the increased use of modularization making it more viable as the activities such as design, documentation, planning, manufacturing and construction can be well-organized (Lu & Korman, 2010). With the advent of model-driven prefabrication, BIM has increased reliance on prefabrication and modular coordination (McGraw Hill Construction, 2011).

In conventional CAD systems, a model represents the building elements only geometrically making the process of integrating rules of modular coordination in a 2D environment cumbersome. On the other side, BIM, that uses information-rich object-orientation in representing parts of a building such as floors, spaces, walls, doors, windows etc. (Bhatt, Borrmann, Amor, & Beetz, 2013; Heloisa Tonissi Buschinelli Goes, Santos, Heloisa, & Buschinelli, 2011), provides an enabling platform for integrating modular coordination rules. BIM allows improved information management over the entire lifecycle of an AEC project. Using two case studies, Lu and Korman demonstrated benefits and challenges of using BIM process with a modular system of construction (Lu & Korman, 2010). One benefit is that BIM allows the addition of parameters to modelling elements, which in turn allows capturing of properties and behaviour in the modelling elements individually and resulting model as a whole.

In BIM, parameters are defined as variables that can store data linked to a modelling element, which allows parametric modelling. Generally, this data pertains to properties of the modelling element, for example, visual, thermal or mechanical properties of a modelling element. In simple terms, parametric modelling is a feature of a BIM authoring tool that allows designers to use mathematical relationships to define constraints and embed domain specific expertise. While regenerating the building geometry in BIM workspace, parameters act as design constraints (Sacks, Eastman, & Lee, 2004). Even complex building systems can be designed and modelled with consistency using parametric modelling capabilities (Cavieres, Gentry, & Al-Haddad, 2011). It eases the process of solid modelling and can automate the generation of building information.

BIM authoring tools help in reducing modelling errors and limit technical flaws by using predefined rules through parametric constraints (V. Singh, Gu, & Wang, 2011). However, these rules are generic such as joint detail between wall and floor and hosting of the window on the wall etc. In terms of architectural and space design, geometrical constraints such as parallel and perpendicular alignment of elements, dimensions of various elements etc. can also be defined. The relationship among neighbouring objects like the alignment of the column along grid lines or associating floor elements with levels can also be defined using parameters (Oosterhuis, 2012). With parametric modelling tool, the users can easily modify designs, generate alternatives and document them at required level of detail (Sacks et al., 2004).

From the point-of-view of the research conducted by the authors, it is important to study the work performed earlier by other researchers. Broadly, ongoing research in this domain can be categorised as follows:

- Using BIM model data after model creation for analysis activities such as energy modelling and simulation (Kota, Haberl, Clayton, & Yan, 2014; Sinha, Sawhney, Borrmann, & Ritter, 2013; Yalcinkaya & Singh, 2015), construction safety (Melzner, Zhang, Teizer, & Bargstädt, 2013)etc.

- Utilising completed BIM model for automated rule checking for activities (Pauwels et al., 2011) such as code compliance, fire safety norms etc.
- Using algorithms and BIM data to generate new design and construction solutions (Abrishami, Goulding, Rahimian, Ganah, & Sawhney, 2014) during the model authoring process

Furthermore, to identify research gaps and frame a research question, existing literature was mapped along the following aspects:

(1) Benefits of BIM Process/Parametric Modelling

(2) Benefits of Modular Coordination/Prefabrication and BIM

(3) Parametric Modelling to Integrate Rules

(4) Automated Design Checking Platforms

(5) Modular Coordination and BIM Integration

This mapping is shown in Table 1.

[Table 1 here]

As described above, previous research has clearly highlighted the need and importance of integrating BIM and modular coordination for model authoring. Concomitant with this, other researchers have also highlighted the role of parametric modelling in BIM for incorporating rules in the design process. However, the conceptual constructs needed for integrating modular coordination rules in a BIM authoring tool have not been addressed. This research presents an approach that addresses this ‘how’ question by using visual programming, parametric modelling capabilities and built-in features of BIM authoring tool to integrate modular coordination. The research by Romcy et al. 2012 is most relevant to this topic, which has presented an approach to generate ceramic block configuration only using programming interface. The complexity of modular coordination rules such as sizing rules, placement rules or joint details, in BIM authoring tools needs to be addressed using the approach that is compatible with these rules. In this research, rules of modular coordination are identified and then incorporated into the BIM authoring tool using features that have been described in the literature detailed above.

Modular Coordination Rules: Overview and Definitions

The modular coordination rules used in the proposed approach can be explained as follows: -

(1) Reference System – The 3D integer lattice works as space frame for hosting modular building components. The building components are placed and aligned to the reference system. The reference planes/ lines in the space frame either have a spacing of a basic module i.e. 100 mm (International Organization for Standardization, 1983a, 1983b) or multi-module i.e. multiple of the module (International Organization for Standardization, 1982, 1983b). For a building, specific multi-module is chosen for X-, Y- or Z- direction as specified in the modular co-ordination standard.

(2) Preferred Sizes – There are preferred sizes for any building components such as doors and windows (International Organization for Standardization, 1974). This allows limiting the number of sizes of particular building component available in the market and ease interchangeability of components (Indian Standards Institution, 1983a).

(3) Alignment System – It is a system to be followed for placing building components in the modular reference system. Various examples are boundary planning, axial planning and so.

(4) 5 mm Rule/ Tolerance – 5 mm rule has been defined for structural elements whether used for creating horizontal or vertical divisions in the building. The dimensions of all the structural elements will be 5 mm less on all modular reference planes. Tolerance is defined for the fabricated components to allow permissible variation in the sizes. Tolerance is permitted for fabricated components to accommodate several variations such as dimensional, setting-out, thermal, positional, manufacturing etc.(Indian Standards Institution, 1983b; International Organization for Standardization, 1979, 1983c)

(5) Joint Details – Joint details are an essential part of the two-dimensional documentation. Modular coordination drawings have specified representation system described in modular coordination standards. Therefore, it is required to embed such specific joint details with rule-based smart building objects to maintain the consistency of drawings with 3D model.

For further reading, international standards on modular coordination mentioned in the reference section can be referred.

4 Research Methodology

The research has been conducted to develop a framework to integrate domain-specific knowledge (for example modular coordination rules based on International Standards) into BIM authoring application. To achieve the objectives of the research, the authors have developed an approach (discussed under section 4.1 & 5: Conceptual Framework for Knowledge Integration) and conducted a case study and an experiment to validate the proposed approach (discussed under sections 4.2 and 6: Validation of the Proposed Approach).

4.1 Conceptual Framework for Knowledge Integration

To accomplish the integration of knowledge extracted from modular coordination into with BIM; rule-based smart building objects and modular reference frame has been developed. This process utilises the built-in functionality of BIM authoring application such as visual programming, smart object development with parametric constraints and referencing system for geometry. Visual programming tools provide a graphical interface to users for developing an algorithm that can automate computational design tasks. A visual programming tool has several advantages such as accessing specific information, defining parametric values from external files apart from automating the design process. Elements having any sequential pattern can be modelled using visual programming tool. Parametric constraint functionality allows developing smart building objects which can modulate itself based on specific values. Also, the referencing system for geometry allows the objects to interact with the neighbouring objects to position itself.

Figure 1 shows the overall framework adopted to achieve the proposed integration. After examining the rules of modular coordination from various standards and modelling process in BIM authoring tool, the study identifies various rules to be incorporated and options available for embedding these in the modelling process. These domain-specific rules such as reference system, preferred sizes, alignment system, 5 mm rule/ tolerance and joint details are incorporated into the BIM authoring tool by object-level development and process-level development as described in the sections 5 and 6 respectively.

[Figure 1 here]

4.2 Validation of Proposed Approach

The authors have developed the proposed approach to facilitate the design documentation and modelling process in BIM environment. To demonstrate the utility of the proposed framework, a case study studying the modelling process of the residential building has been performed. Also, an experiment has been conducted with 10 users and their experience with the proposed framework has been recorded and compared with the traditional experiences. The validation process, the cased study and the experiment will be discussed under section 6.

The overall object and process level development needs a BIM authoring tool with parametric modelling capabilities and compatible visual programming tools. To demonstrate both object and process level development using the conceptual approach proposed by the authors, BIM authoring tool for building design from Autodesk Inc. i.e. Revit and visual programming tool Dynamo was selected.

5 Conceptual Framework for Knowledge Integration

The proposed framework for knowledge integration requires Object Level Developments (sub section 5.1) and Process Level Developments (sub section 5.2).

5.1 Object Level Developments

The modular coordination standards primarily define rules for sizing the building components and their placement in a reference system. The object level developments include modelling of rule-based smart building objects (for sizing) and modular reference frame (for placing). Figures 2 shows the development process of integrating modular coordination rules. Visual programming tool, assistive messages and catalogue of (building component) sizes are used in the background to assist the modeller in the building component sizing process. For assistance in placing and alignment of building components within the modular reference frame, reference lines/planes are created (Manav Mahan Singh, 2014; Manav Mahan Singh, Sawhney, & Borrmann, 2015) as discussed in sections 5.1.1 and 5.1.2.

[Figure 2 here]

5.1.1 Development of Rule-based Smart Building Objects

For integration of modular coordination rules, various building components such as doors, windows, slab panels etc. were developed. These are customizable under the rules of modular coordination, will adapt to changes made in the model, allow data update in quantity schedule and incorporate details. These properties of modelled building component will allow to identify them as rule-based smart building objects. These objects are modelled using built-in functionality of BIM authoring tool primarily parametrical modelling. Figure 3 shows various rules prescribed for modular elements (wall/slab panels) with options available to incorporate rules of modular coordination. The system guides the modeller through the selection of possible dimensions for length, width, thickens, opening size and position of these elements via assistive messages. The horizontal and vertical alignment and height of components can be associated with a modular reference frame (modular grids and levels) while details such as joints, tolerance and 5 mm rule for structural elements are captured during the modelling process.

[Figure 3 here]

(1) Visual Programming Tool for Sizing

Visual programming tool has been used to select the value of a parameter from a set of values stored in the external data file. Values such as submodular increment, preferred dimension for horizontal coordination or tolerances are stored in a separate spreadsheet or generated based on the mathematical equation and chosen using the visual programming tool. The visual programming tool has been used as a facilitator to select the size for dimensions of any building component. As shown in figure 4, one part of the visual program generates the values and converts it to list. Then, the query node collects a specific value from the list. The last part inserts that value as the value of the parameter for selected modelling element type.

[Figure 4 here]

(2) Assistive Messages for Sizing

The suggestive information for adjusting values of the parameter has been provided to the user, in case, there is a deviation from a specified set of values. The conditional statements have been used in formulas with Yes/No parameter types to control the visibility of text messages. The appearance of these assistive messages in the project environment indicates the dimension of the object is not per rules. As described in figure 5, first create assistive messages while modelling the objects, then associate a visibility (Yes/No) parameter with it. After that, create a conditional statement to control the value of yes/no parameter. The appearance of assistive messages in the project environment warns the user about violation of modular coordination rules and assist the user to input appropriate size of the element.

[Figure 5 here]

(3) Catalogue of Sizes for Modular Doors/Windows

Several combinations of values for parameters are possible for modelling elements such as doors and windows under modular coordination rules. A suitable set of values for parameters can be generated using spreadsheet application and only specific values can be chosen while importing the component into the project environment. In this study, *"type catalogue"* option is utilised to generate a combination of length and height for doors and windows available under modular coordination standards. Figure 6 shows .csv file, containing a possible set of width and height of doors and windows can be associated with objects to generate set of values for parameters.

[Figure 6 here]

5.1.2 Development of Modular Reference Frame

The modular reference frame is an important prerequisite to commencing design according to modular coordination standards. The modular reference frame consists of planes represented by lines along the x, y, and z directions. These planes work as a reference for placing building components such as a wall, window etc. References can be created through object level development within the BIM authoring tool. In the proposed framework, this is accomplished by using visual programming and associating reference planes with rule-based smart building objects, is explained as follows:-

(1) Visual Programming for Modular Reference Frame

As explained in section 4.1, visual programming tool can be used to model elements having a sequential pattern. To generate a modular grid, the algorithm can be developed and translated into the program using visual program tool. For modular reference planes in plan view, column grids have been created in horizontal plane and levels have been created in the vertical plane. Figure 7 shows the program used to create column grids in the horizontal plane. A user selects the multi-module for the direction and number of modular grids in that direction. The program creates a grid of line in X- and Y-directions as per the user's inputs.

[Figure 7 here]

To create reference planes in a vertical plane, the user needs to create levels. There is a set of values that can be used as modular floor height as per modular coordination standards. Figure 8 shows the visual program used to create levels in the vertical plane. A user can select a specific value for the level which is added to the elevation of the previous level to define the elevation of next level.

[Figure 8 here]

(2) Reference Planes for Alignment

For this research, axial placement of structural elements has been chosen. Figure 9 shows the modelled building components, which have reference lines to align it to the modular reference frame. The reference lines with the modelled objects interact with the modular grids and guides the placement of modular objects in the reference system.

[Figure 9 here]

Construction details such as joining details, tolerance for various elements and 5 mm rule for structural elements are integrated while modelling rule-based smart building objects. While modelling, and placing the building components, reference lines are used to align objects to the grid lines with appropriate distance. Furthermore, the tolerance values for building elements can be adjusted to data provided by manufacturers using visual programming tool.

5.2 Process Level Developments

The use of BIM is not only to enhance the modelling process to create computational 3D geometry but to improve the overall design and construction process also. The process level developments include enhanced modelling process, generation of 2D drawings, 3D visualisation, quantity take-off and information sharing. The principal advantage of using rule-based smart building objects is the use of a single model to extract precise and coherent 2D drawings along with 3D models in BIM environment (Lee & Ha, 2013). Rule-based smart building objects guides the designer throughout the design process by assistive messages, visual programs and alignment references. This further helps in generating 2D drawings, 3D visualisations, quantity take-off and information sharing using features already available with BIM authoring tool. Figure 10 explains that geometrical, information sharing and identity parameters are integrated into rule-based smart building objects which enhance the documentation activities in BIM environment.

[Figure 10 here]

The integration of geometrical, parametrical constraints alongside identity and information sharing parameters with rule-based smart building objects is aimed to enhance the design activities such as generation of various drawings, views, quantity take-off and information sharing. Visual programming tool to create modular reference frame and its interaction with rule-based smart building objects help in the modelling process.

6 Validation of Proposed Approach

The process level developments are also required to realise the maximum benefits of modelling in BIM environment. This section details out process level development using the proposed framework. First, the modelling process using the proposed framework, the process starts with the selection of multi-modules in each direction, after which grid lines in X- and Y- directions are generated using visual programming tool. To create reference lines in Z- direction, the visual program discussed in section 5.1.2 has been used. This creates a three-dimension lattice in the workspace which serves as a reference for the rule-based smart building object to be placed. Rule-based smart building objects (loadable families in Autodesk Revit) can be inserted at their centre lines since these objects are modelled with reference lines for their alignment as discussed in section 5.1.2. The sizes of these inserted building objects can be adjusted according to modular coordination rules as discussed in section 5.1. The whole building can be modelled by inserting these rule-based smart building objects. Since, these objects contain all the relevant information for generating drawings, visualisation and joint details, these activities can be done effortlessly. Also, quantity take-off and information sharing parameters helps in creating the schedules using built-in features of BIM authoring tool. The usefulness of the proposed approach is documented using a case study under section 6.1 and user experience under section 6.2.

6.1 A Case Study of Modelling Process

A residential building has been modelled using rule-based smart building objects developed as part of this research to explain the process level developments and validate the presented approach. Generation of 2D drawings, details, visualization and quantity scheduling process has been discussed as follows: -.

(1) Generation of 2D Drawings, Design Details and Visualisation

Since the available rule-based smart building objects under the proposed approach have all the details as explained under object-level developments, a single model can be used for preparing 2D drawing, 2D drawings of design details and 3D visualisation. It makes the process automated, eliminating the need of different models to be updated for design changes. Subsequently, this will also reduce inconsistencies in the drawings. After modelling the residential facility, using rule-based smart building objects, floor plans and sections (as shown in figure 11) can be generated:

[Figure 11 here]

Figure 12 shows 2D design details of joints, which gets updated automatically as changes occur in the model.

[Figure 12 here]

Figure 13 shows an interior view of the facility, the view clearly shows building elements and joints between them. It is in complete coordination with 2D drawings. The details are inbuilt with prefabricated elements that make the process completely automated for all activities, eliminating the need of different models to be updated after design changes.

[Figure 13 here]

(2) Quantity Take-off Process and Information Sharing

With the help of parameters associated with building objects, the quantity take-off and information sharing process can also be streamlined. The geometrical parameters such as length, thickness etc. are useful for quantity take-off process. Figure 14 shows a schedule of prefabricated components used for the building is generated using the developed model using rule-based smart building objects.

[Figure 14 here]

The identity parameters such as Mark, URL, Manufacturer, Opening Description and Description are associated to every prefabricated component for effective exchange of information. Especially, the URL parameter is quite useful to create a link to the online resource to integrate more information. As explained in figure 15, the building component details can be uploaded in two file formats having certain advantages and disadvantages.

(1) .dwfx format (A web-friendly format for viewing drawings)

(2) .rfa format (A proprietary file format)

[Figure 15 here]

All these parameters are created as shared parameters so that they can appear on the schedule. The identity parameters will be helpful in preparing the fabrication schedule also.

6.2 An Experiment Documenting Users Experience

To validate the proposed framework, the authors have conducted an experiment with ten users and document their modelling experience on a Likert scale of 1 to 5. Their responses have been mapped against time, ease in modelling, model quality and ability to generate drawings and quantity schedule. The modelling experience of ten users is compared with a traditional user who has modelled the same building in BIM without using the framework. Figure 16 summarises the modelling experience of the users using traditional approach and the proposed framework. The time spent in the modelling process using the proposed approach averaged around 40 minutes compare to 2 hours 8 minutes in the traditional approach. The bottom left graph in figure 16 shows the comparison of time taken by the traditional user to users modelling in the proposed framework. The table in figure 16 shows the responses from individual on their modelling experience against time spent in modelling, ease of modelling, implementation of modular coordination rules, modelling errors/ mistakes, ease in generating drawings/ details, ease in generating quantity schedule and overall model quality. The graph on right side of the figure shows the comparison of the responses from the traditional user to users modelling in the proposed framework.

[Figure 16 here]

The users have experienced approximate 70%-time saving compared to the traditional approach. The overall model quality has improved due to the use of the single model for generating all the drawings. The modelled building components facilitated implementation of modular coordination rules without referring to the standards. The schedule of prefabricated panels gets prepared with the modelling process to reduce users' efforts. During the modelling in the traditional approach, the user has modelled the building, generated details at the joint and created the quantity schedule manually. Also, making the changes in the model requires his expertise to update all the drawings and quantity schedule.

7 Research Implications

The proposed framework demonstrate that modular coordination rules can be incorporated with BIM authoring application to facilitate modelling as well as design documentation process. The research paves the way to integrate more domain specific rules such as acoustic considerations, building bye-laws or national building standards and guidelines for site layout in to BIM authoring application to ease the modelling process (Kumar & Cheng, 2015). Although, all of these standards cannot be associated with BIM tool using the approach described in this paper. There are more options, such as Application Programming Interface (API) or performance checking with IFC format (Hu, Zhang, Wang, & Kassem, 2016; Pauwels et al., 2011). API can be used to develop plugins to automate any typical design process, access model graphical data, access model parametrical data, collecting data for other applications and performing analysis (Autodesk Inc., 2014, 2017; Lopez, 2011; M M Singh, Sawhney, Sharma, & Kumari, 2016).

8 Conclusions

The study explains the process of integrating the rules of modular coordination in BIM authoring tools using rule-based smart building objects, parametric constraints and visual programming. By integrating engineering rules, the user is guided through the design and modelling process of built environment. Furthermore, it can enhance the design documentation process, potentially enhancing the efficiency of the process. By incorporating project specific rules, the process of utilising BIM on the project can be streamlined thereby making adoption of BIM easier. Through, process level developments, the project also explains a systematic process to generate 2D drawings from a 3D model, communication of design details, performing quantity take-off, and effective information sharing under the modular coordination regime. The built-in rules of modular coordination help in significantly reducing modelling errors. These integrated rules can improve the design quality and streamline the overall design process.

References

Abrishami, S., Goulding, J., Rahimian, F. P., Ganah, A., & Sawhney, A. (2014). G-BIM Framework and Development Process for Integrated AEC Design Automation. *Procedia Engineering*, *85*, 10–17. http://doi.org/10.1016/j.proeng.2014.10.523

Autodesk Inc. (2014). Revit 2014 Platform API Developers Guidelines. Retrieved November 17, 2013, from http://wikihelp.autodesk.com/Revit/enu/2014/Help/3665-Developers

Autodesk Inc. (2017). Autodesk - My First Plug-in Training. Retrieved April 23, 2017, from http://usa.autodesk.com/adsk/servlet/index?siteID=123112&id=16777469

Bhatt, M., Borrmann, A., Amor, R., & Beetz, J. (2013). Architecture, computing, and design assistance. *Automation in Construction*, *32*(29), 161–164. http://doi.org/10.1016/j.autcon.2013.01.001

Borrmann, A., & Rank, E. (2010). Query Support for BIMs using Semantic and Spatial Conditions. In *Handbook of Research on Building Information Modeling and Construction Informatics* (pp. 405–450). IGI Global. http://doi.org/10.4018/978-1-60566-928-1.ch018

Cavieres, A., Gentry, R., & Al-Haddad, T. (2011). Knowledge-based parametric tools for concrete masonry walls: Conceptual design and preliminary structural analysis. *Automation in Construction*, *20*(6), 716–728. http://doi.org/10.1016/j.autcon.2011.01.003

Chiang, Y.-H., Hon-Wan Chan, E., & Ka-Leung Lok, L. (2006). Prefabrication and barriers to entry—a case study of public housing and institutional buildings in Hong Kong. *Habitat International*, *30*(3), 482–499. http://doi.org/10.1016/j.habitatint.2004.12.004

Choo, H. J., Hammond, J., Tommelein, I. D., Austin, S. A., & Ballard, G. (2004). DePlan: a tool for integrated design management. *Automation in Construction*, *13*(3), 313–326. http://doi.org/10.1016/j.autcon.2003.09.012

Ding, L., Zhou, Y., & Akinci, B. (2014). Building Information Modeling (BIM) application framework: The process of expanding from 3D to computable nD. *Automation in Construction*, *46*, 82–93. http://doi.org/10.1016/j.autcon.2014.04.009

Eastman, C., Sacks, R., & Lee, G. (2004). Functional modeling in parametric CAD systems. In *Proceedings of Generative CAD Systems (G-CAD) Conference, Carnegie Mellon University*. Pittsburgh. http://doi.org/10.1.1.93.398

Heloisa Tonissi Buschinelli Goes, R., Santos, E. T., Heloisa, R., & Buschinelli, T. (2011). Design Coordination With Building Information Modeling : A Case Study. In *Proceedings of the CIB W78-W102 2011* (pp. 26–28). Sophia Antipolis, France.

Hergunsel, M. F. (2011). *Benefits of Building Information Modeling*. *Design*. Retrieved from http://www.wpi.edu/Pubs/ETD/Available/etd-042011-135239/unrestricted/MHergunsel_Thesis_BIM.pdf

Hu, Z.-Z., Zhang, X.-Y., Wang, H.-W., & Kassem, M. (2016). Improving interoperability between architectural and structural design models: An industry foundation classes-based approach with web-based tools. *Automation in*

Construction, *66*, 29–42. http://doi.org/10.1016/j.autcon.2016.02.001

Indian Standards Institution. IS 10600 - Recommendations for Modular Co-Ordination - Principles and Rules, Pub. L. No. IS 10600 (1983). India.

Indian Standards Institution. IS 4993 - Glossary of Terms relating to Modular Coordination (1983). India.

International Organization for Standardization. ISO 2776 - Modular Coordination - Coordinating Sizes for Doorsets - External and Internal (1974).

International Organization for Standardization. ISO 3443 - Tolerances for Building (Part 1) - Basic Principles for Evaluation and Specification (1979).

International Organization for Standardization. ISO 6511 - Building Construction - Modular Floor Plane for Vertical Dimensions (1982).

International Organization for Standardization. ISO 1006 - Building Construction - Modular Coordination - Basic Module (1983).

International Organization for Standardization. ISO 1040 - Building Construction - Modular Coordination - Multimodules for Horizontal Coordinating Dimension (1983).

International Organization for Standardization. ISO 1791 - Building Construction - Modular Coordination - Vocabulary (1983).

International Organization for Standardization. ISO 2848 - Building construction - Modular coordination - Principles and rules, Pub. L. No. ISO 2848 (1984).

Kota, S., Haberl, J. S., Clayton, M. J., & Yan, W. (2014). Building Information Modeling (BIM)-based daylighting simulation and analysis. *Energy and Buildings*, *81*, 391–403. http://doi.org/10.1016/j.enbuild.2014.06.043

Kumar, S. S., & Cheng, J. C. P. (2015). A BIM-based automated site layout planning framework for congested construction sites. *Automation in Construction*, *59*, 24–37. http://doi.org/10.1016/j.autcon.2015.07.008

Lawson, B. (2005). Oracles, draughtsmen, and agents: the nature of knowledge and creativity in design and the role of IT. *Automation in Construction*, *14*(3), 383–391. http://doi.org/10.1016/j.autcon.2004.08.005

Lee, S., & Ha, M. (2013). Customer interactive building information modeling for apartment unit design. *Automation in Construction*, *35*, 424–430. http://doi.org/10.1016/j.autcon.2013.05.026

Lopez, J. M. S. (2011). *Calculation and representation of structural reinforcement in Building Information Models using Revit Structure and SOFiSTiK*. Technical University, Munich.

Lu, N., & Korman, T. (2010). Implementation of Building Information Modeling (BIM) in Modular Construction: Benefits and Challenges. In *Construction Research Congress 2010* (Vol. 1, pp. 1136–1145). Reston, VA: American Society of Civil Engineers. http://doi.org/10.1061/41109(373)114

March, L. (2003). Rudolph M. Schindler. Space Reference Frame, Modular Coordination and the "Row." *Nexus Network Journal*, *5*(2), 48–59. http://doi.org/10.1007/s00004-003-0016-x

McGraw-Hill Construction. (2014). *The Business Value of BIM for Construction in Major Global Markets: How contractors around the world are driving innovation with Building Information Modeling*. (H. M. Bernstein, S. A. Jones, M. A. Russo, & D. Laquidara-Carr, Eds.)*SmartMarket Report*. Bedford, MA, USA. Retrieved from http://static-dc.autodesk.net/content/dam/autodesk/www/solutions/building-information-modeling/construction/business-value-of-bim-for-construction-in-global-markets.pdf

McGraw Hill Construction. (2011). *Prefabrication and Modularization: Increasing productivity in the construction industry*. *SmartMarket Report*. Bedford, MA, USA.

Melzner, J., Zhang, S., Teizer, J., & Bargstädt, H.-J. (2013). A case study on automated safety compliance checking to assist fall protection design and planning in building information models. *Construction Management and Economics*, *31*(6), 661–674. http://doi.org/10.1080/01446193.2013.780662

Monteiro, A., & Poças Martins, J. (2013). A survey on modeling guidelines for quantity takeoff-oriented BIM-based design. *Automation in Construction*, *35*, 238–253. http://doi.org/10.1016/j.autcon.2013.05.005

Oosterhuis, K. (2012). Simply complex, toward a new kind of building. *Frontiers of Architectural Research*, *1*(4), 411–420. http://doi.org/10.1016/j.foar.2012.08.003

Pauwels, P., Van Deursen, D., Verstraeten, R., De Roo, J., De Meyer, R., Van de Walle, R., & Van Campenhout, J. (2011). A semantic rule checking environment for building performance checking. *Automation in Construction*, *20*(5), 506–518. http://doi.org/10.1016/j.autcon.2010.11.017

Romcy, N., Cardoso, D., Bertini, A., & André, P. (2012). Customização de aplicativo BIM , segundo princípios da Coordenação. In *Proceedings of the 16th Iberoamerican Congress of Digital Graphics*.

Sacks, R., Eastman, C. M., & Lee, G. (2004). Parametric 3D modeling in building construction with examples from precast concrete. *Automation in Construction*, *13*(3), 291–312. http://doi.org/10.1016/S0926-5805(03)00043-8

Sawhney, A. (2014). *International BIM Implementation Guide* (1st ed.). London: Royal Institution of Chartered Surveyors (RICS).

Sawhney, A., & Maheswari, J. U. (2013). Design Coordination Using Cloud-based Smart Building Element Models. *International Journal of Computer Information Systems and Industrial Management Applications*, *5*, 445–453. Retrieved from www.mirlabs.net/ijcisim/index.html

Singh, M. M. (2014). *Modular Coordination using Building Information Modelling (BIM) Application*. Indian Institute of Technology.

Singh, M. M., Sawhney, A., & Borrmann, A. (2015). Modular Coordination and BIM: Development of Rule Based Smart Building Components. *Procedia Engineering*, *123*, 519–527. http://doi.org/10.1016/j.proeng.2015.10.104

Singh, M. M., Sawhney, A., Sharma, V., & Kumari, S. P. (2016). EXPLORING POTENTIALS OF USING BIM DATA FOR FORMWORK DESIGN THROUGH API DEVELOPMENT. *Proceedings of ID@50 Integrated Design Conference*.

Singh, V., Gu, N., & Wang, X. (2011). A theoretical framework of a BIM-based multi-disciplinary collaboration platform. *Automation in Construction*, *20*(2), 134–144. http://doi.org/10.1016/j.autcon.2010.09.011

Sinha, S., Sawhney, A., Borrmann, A., & Ritter, F. (2013). Extracting Information from Building Information Models for Energy Code Compliance of Building Envelope. In *Proceedings of the RICS COBRA Conference 2013* (pp. 1–16). Retrieved from http://www.cms.bgu.tum.de/publications/2013_Sinha_COBRA.pdf%5Cnhttp://www.rics.org/research

The Modular Building Institute. (2010). *Improving Construction Efficiency & Productivity with Modular Construction*. Charlottesville, USA.

Yalcinkaya, M., & Singh, V. (2015). Patterns and trends in Building Information Modeling (BIM) research: A Latent Semantic Analysis. *Automation in Construction*, *59*, 68–80. http://doi.org/10.1016/j.autcon.2015.07.012

List of Figures

Figure 1

Click here to download Figure Figure 1.pdf

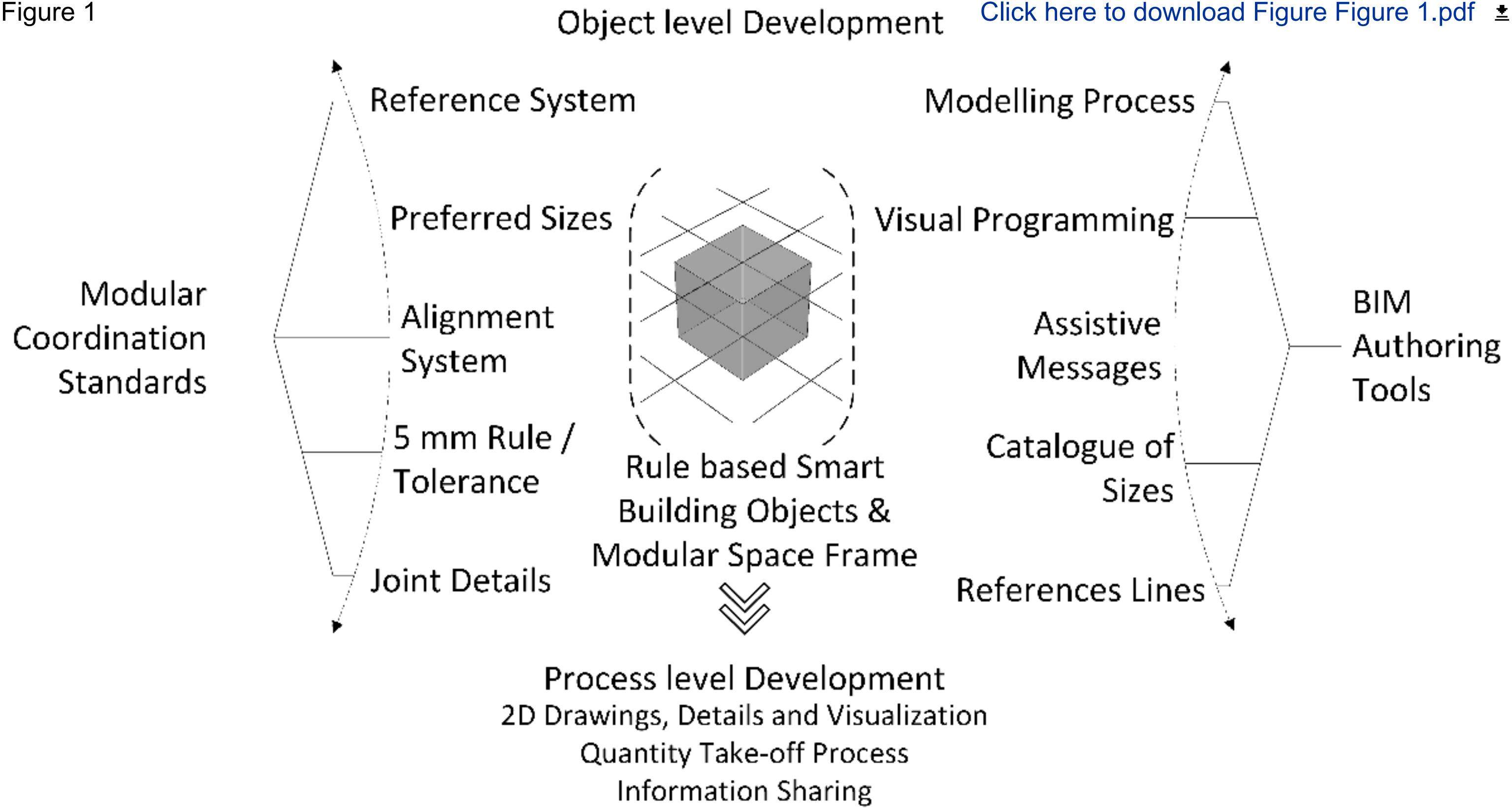


Figure 2

Click here to download Figure Figure 2.pdf

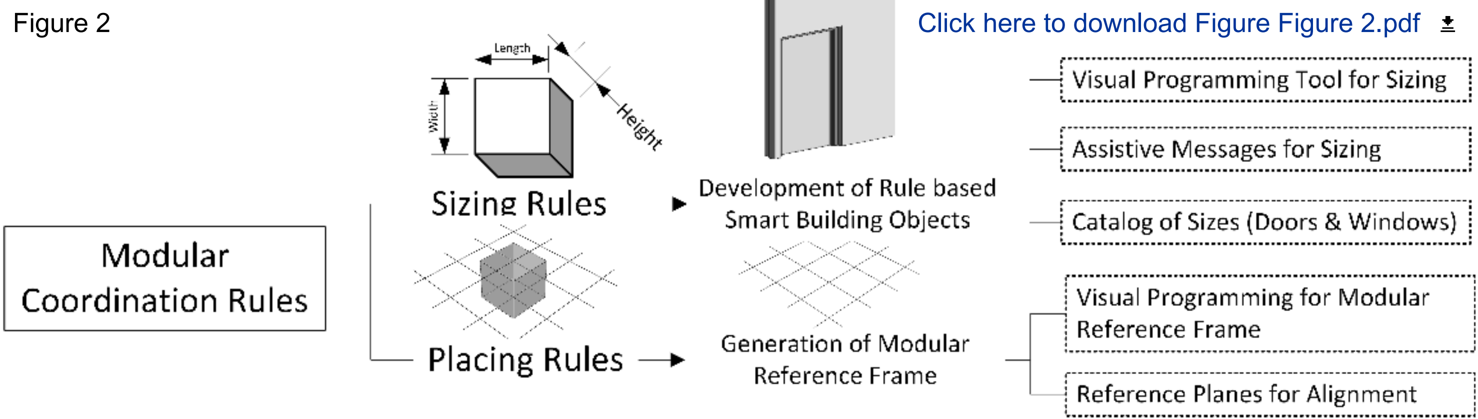


Figure 3

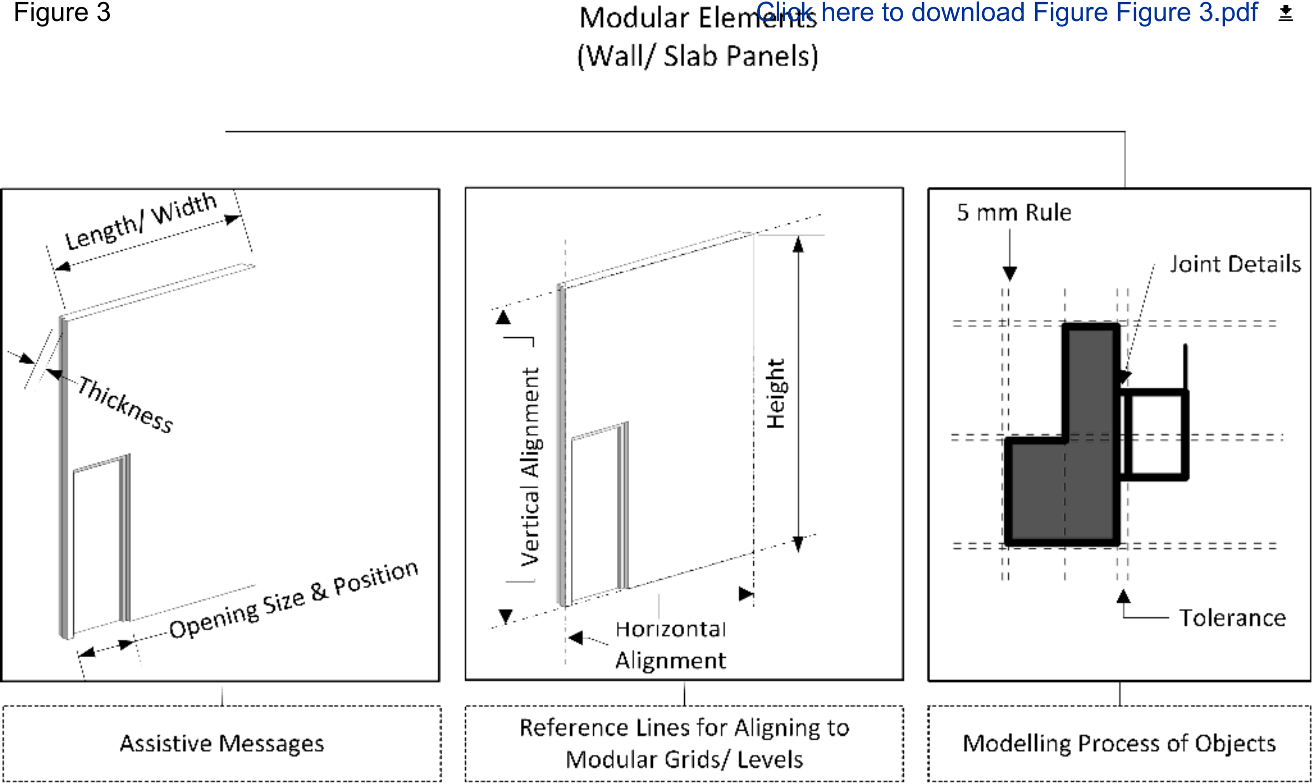

Modular Elements
(Wall/ Slab Panels)
Length/ Width
Thickness
Opening Size & Position
Vertical Alignment
Height
Horizontal
Alignment
5 mm Rule
Joint Details
Tolerance
Assistive Messages
Reference Lines for Aligning to
Modular Grids/ Levels
Modelling Process of Objects

Figure 4

Click here to download Figure Figure 4.pdf

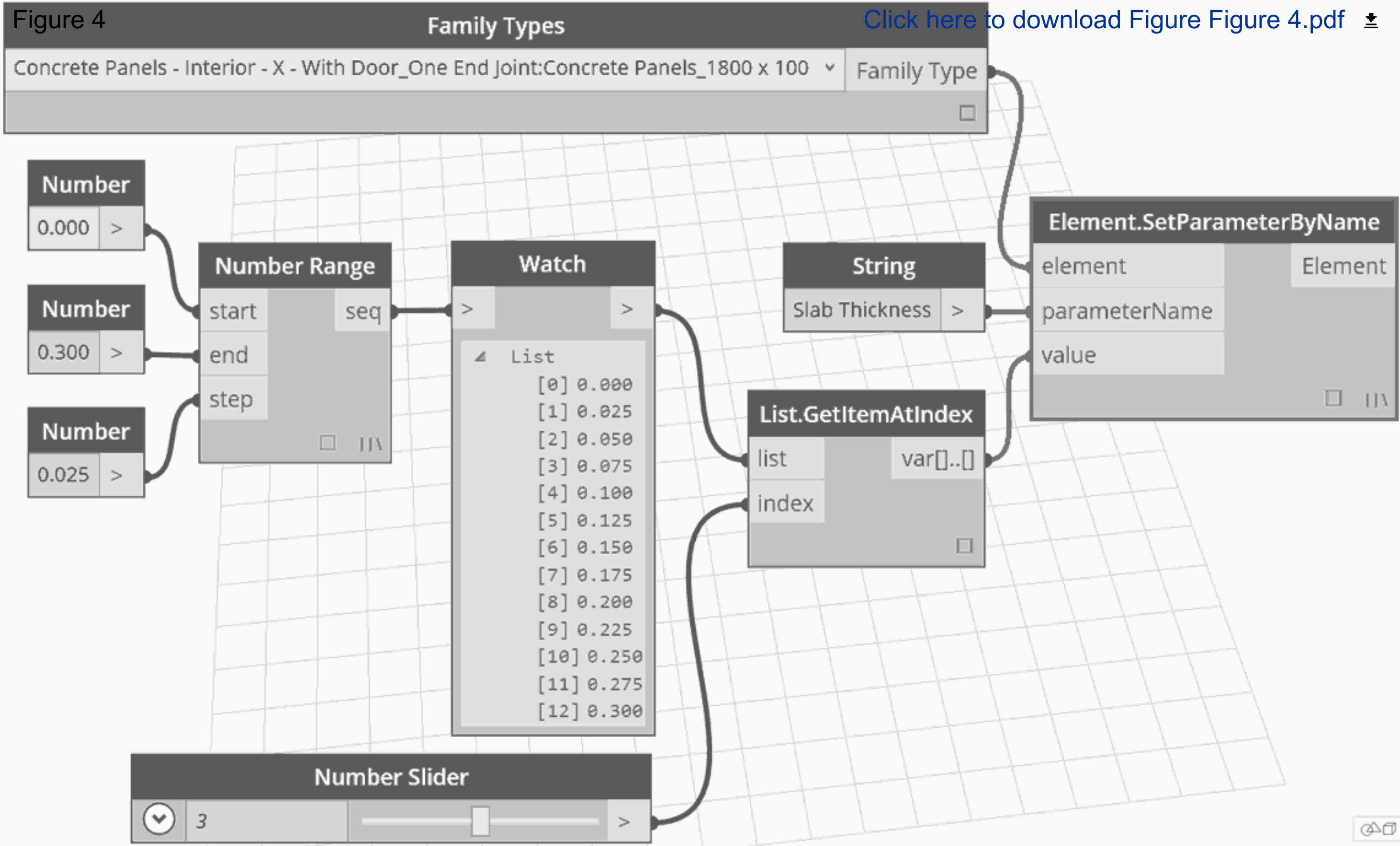


Figure 5

Click here to download Figure Figure 5.pdf

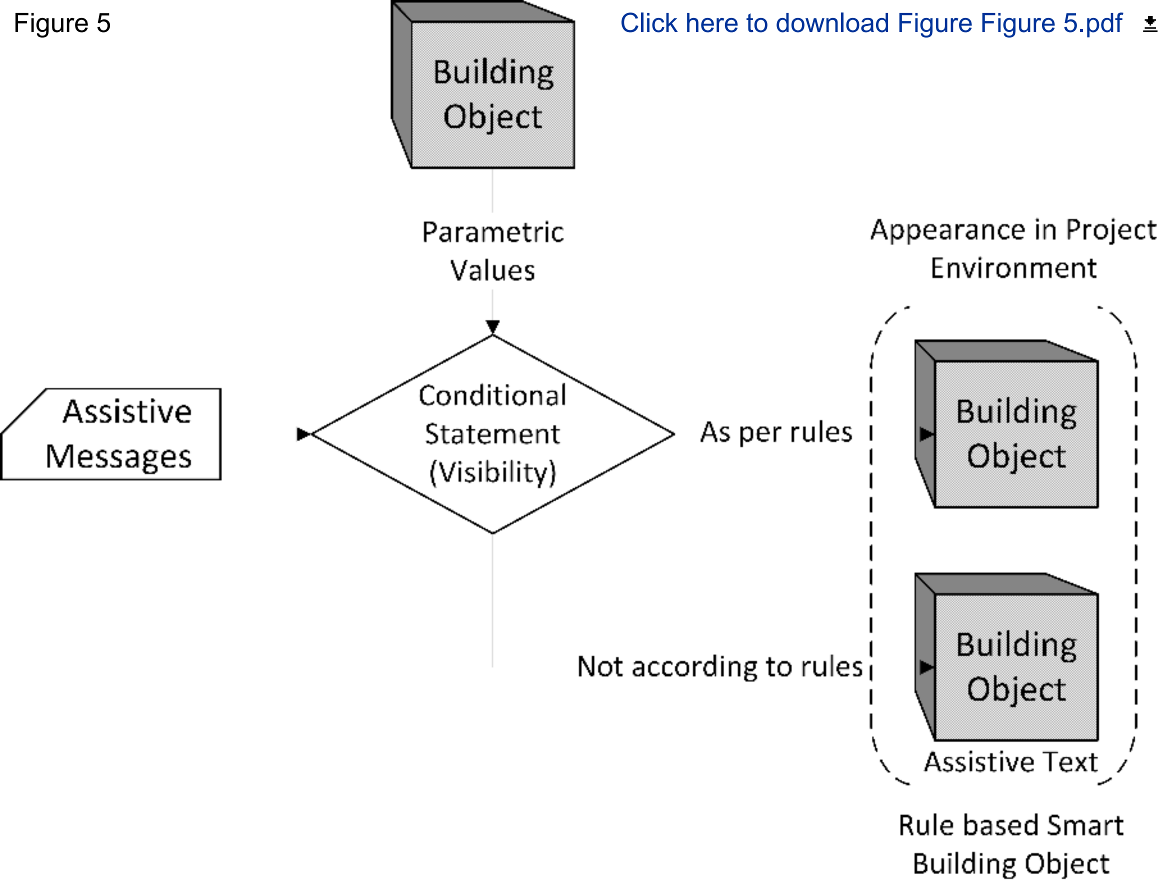


Figure 6

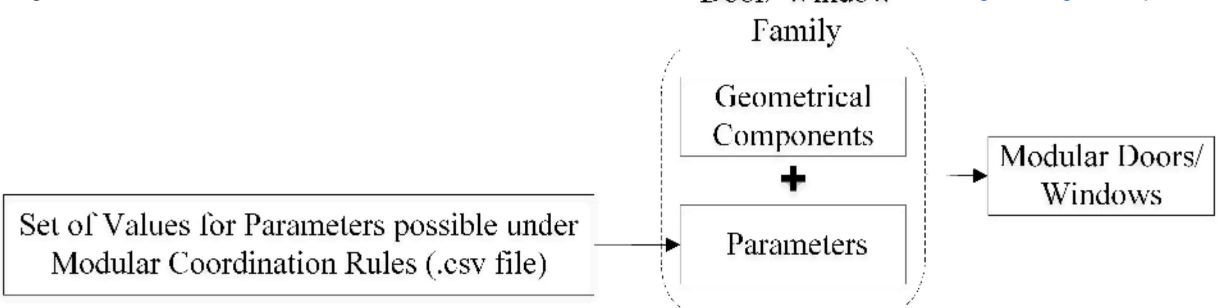
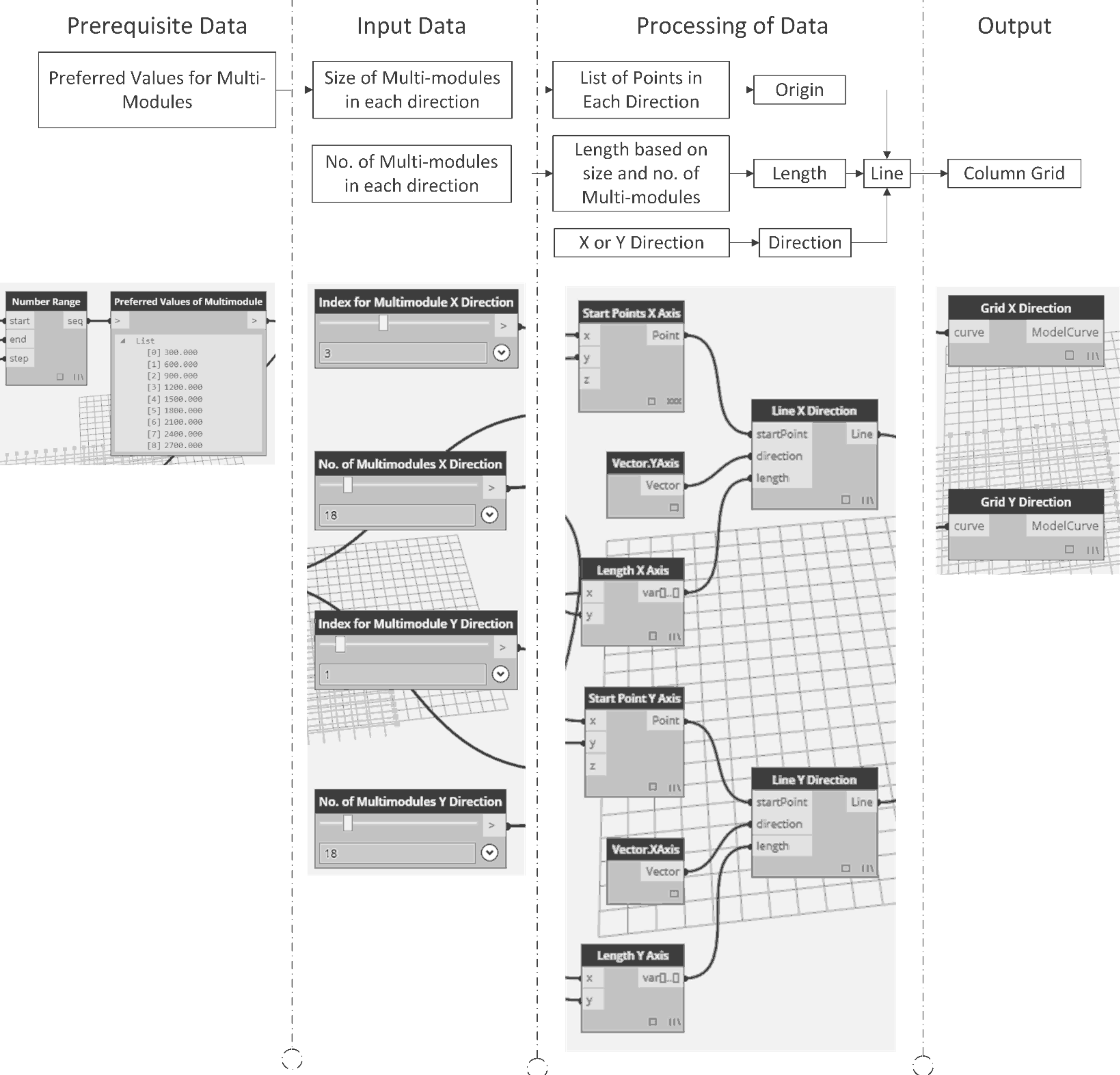

Door/ Window
Family
Geometrical
Components
+
Parameters
Modular Doors/
Windows
Set of Values for Parameters possible under
Modular Coordination Rules (.csv file)

Figure 7



Prerequisite Data
Input Data
Processing of Data
Output
Preferred Values for Multi-Modules
Size of Multi-modules in each direction
No. of Multi-modules in each direction
List of Points in Each Direction
Length based on size and no. of Multi-modules
X or Y Direction
Origin
Length
Direction
Line
Column Grid
Number Range
start
end
step
seq
Preferred Values of Multimodule
List
[0] 300.000
[1] 600.000
[2] 900.000
[3] 1200.000
[4] 1500.000
[5] 1800.000
[6] 2100.000
[7] 2400.000
[8] 2700.000
Index for Multimodule X Direction
3
No. of Multimodules X Direction
18
Index for Multimodule Y Direction
1
No. of Multimodules Y Direction
18
Start Points X Axis
x
y
z
Point
Vector.YAxis
Vector
Line X Direction
startPoint
direction
length
Line
Length X Axis
x
y
var[]..[]
Start Point Y Axis
x
y
z
Point
Line Y Direction
startPoint
direction
length
Line
Vector.XAxis
Vector
Length Y Axis
x
y
var[]..[]
Grid X Direction
curve
ModelCurve
Grid Y Direction
curve
ModelCurve

Figure 8

Click here to download Figure Figure 8.pdf

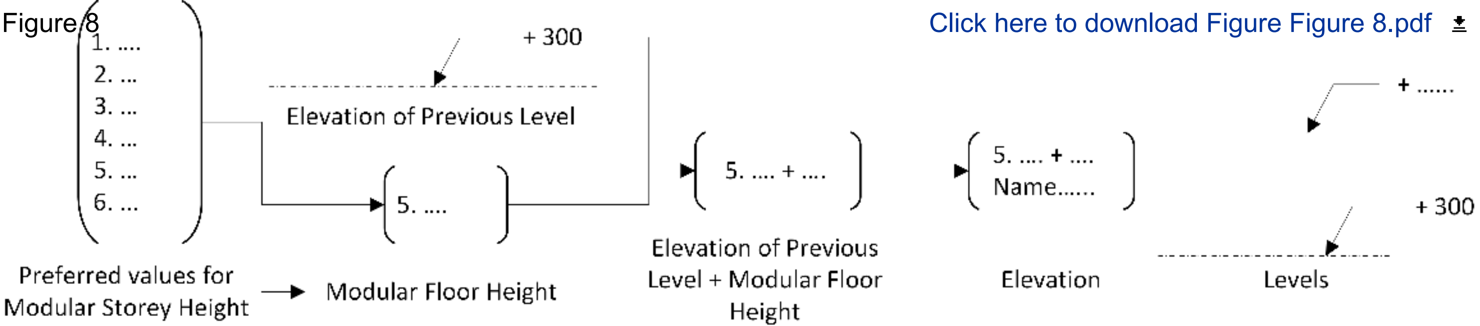


Figure 9

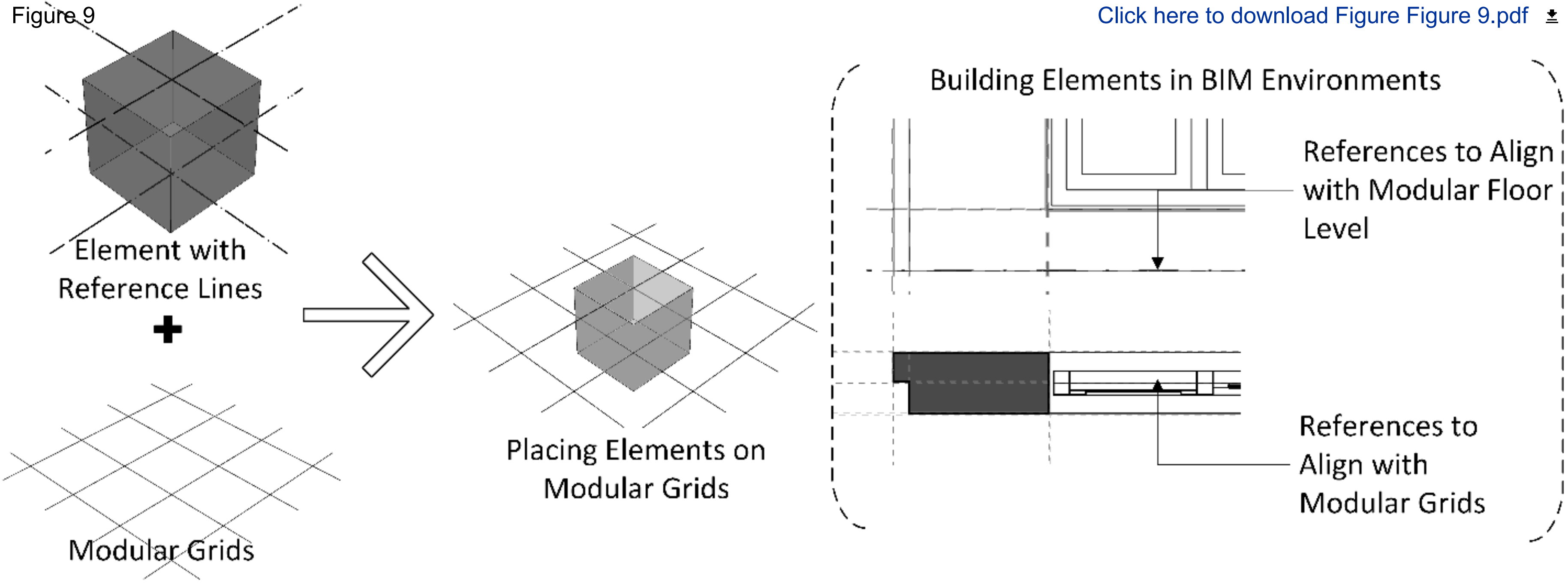

Element with
Reference Lines
Modular Grids
Placing Elements on
Modular Grids
Building Elements in BIM Environments
References to Align
with Modular Floor
Level
References to
Align with
Modular Grids

Figure 10

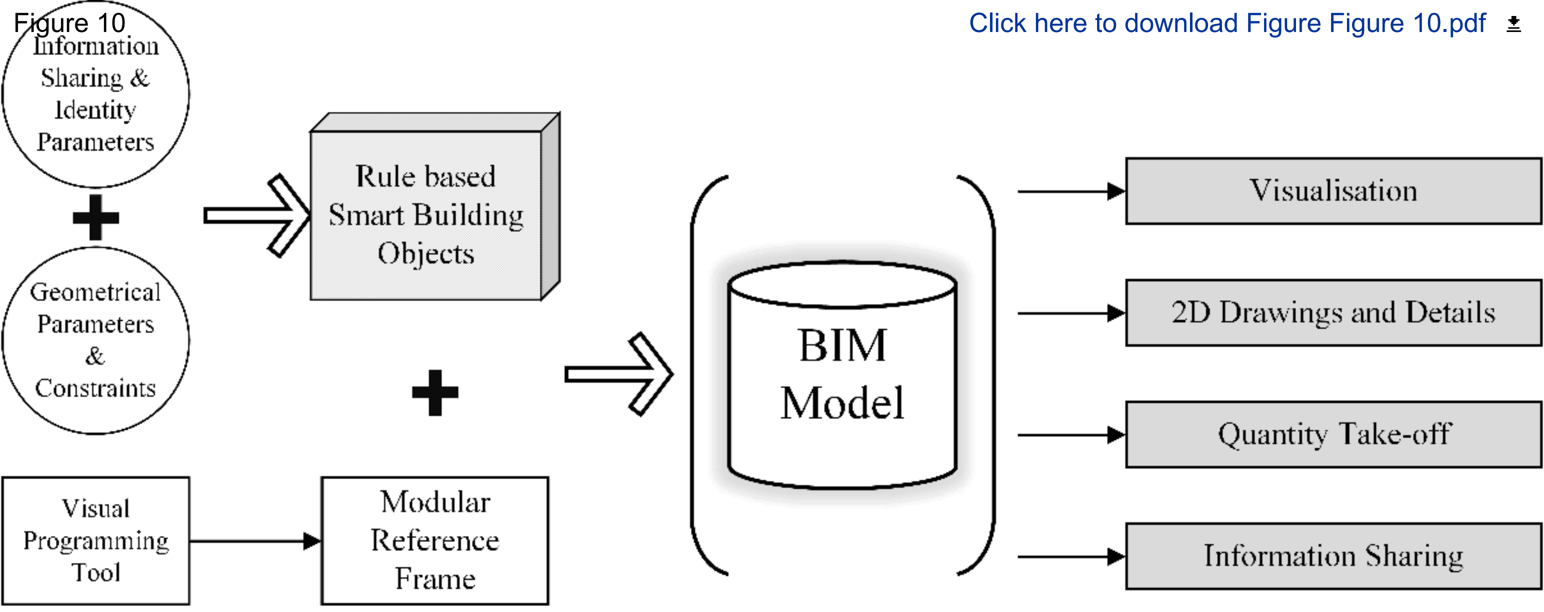
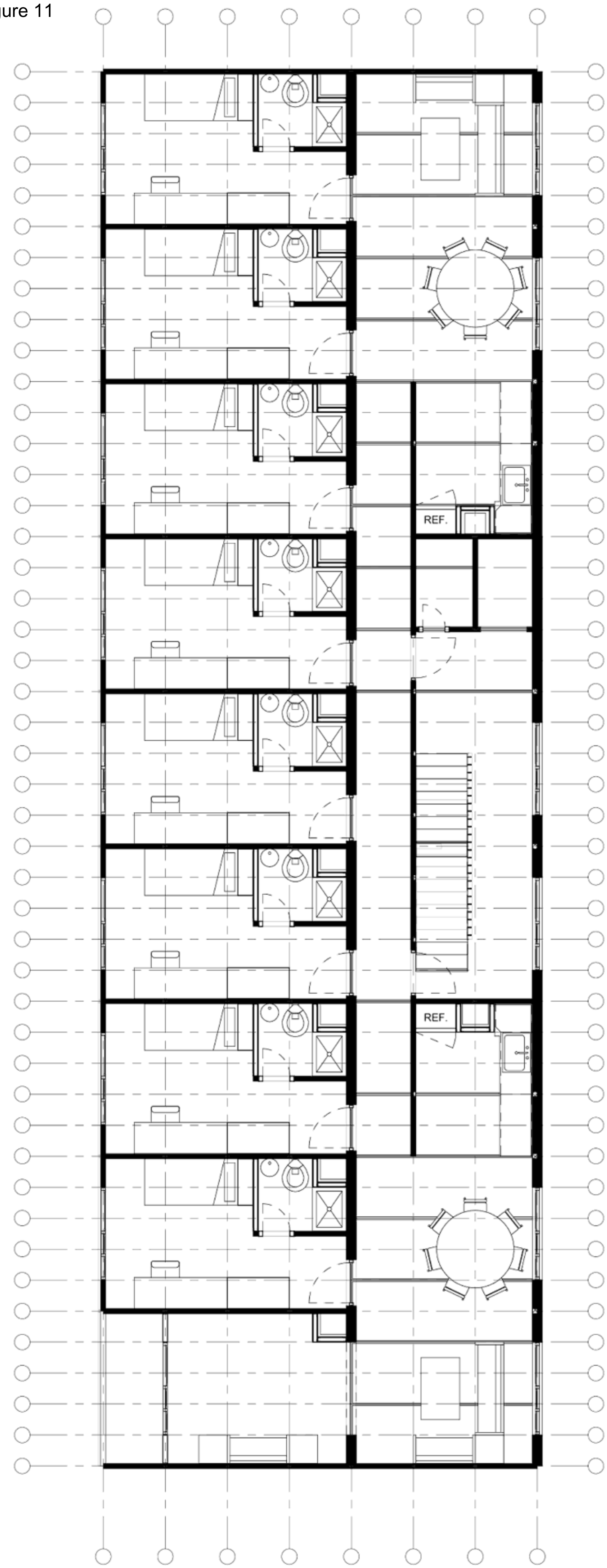
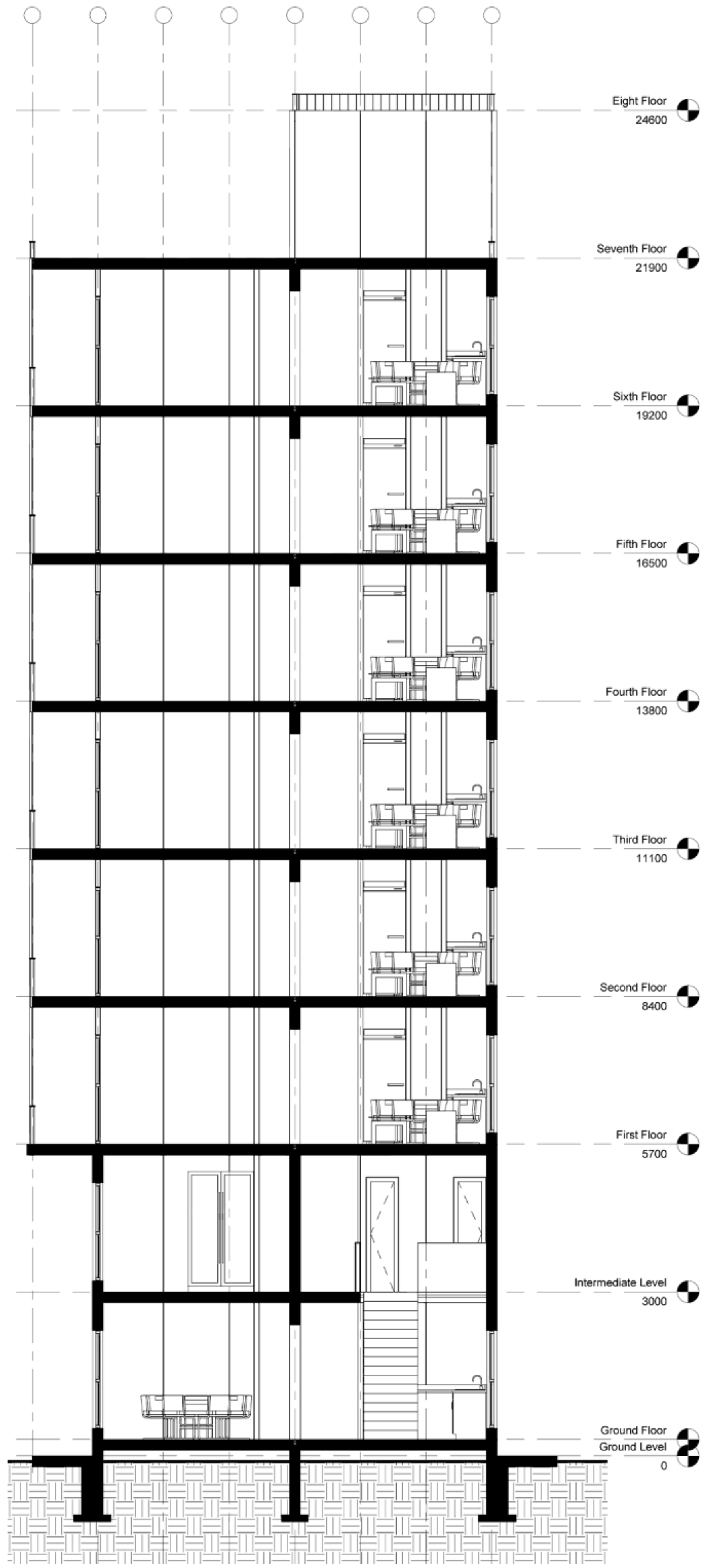

Information Sharing & Identity Parameters
Geometrical Parameters & Constraints
Rule based Smart Building Objects
Visual Programming Tool
Modular Reference Frame
BIM Model
Visualisation
2D Drawings and Details
Quantity Take-off
Information Sharing

Figure 11



FLOOR PLAN



SECTION

Figure 12

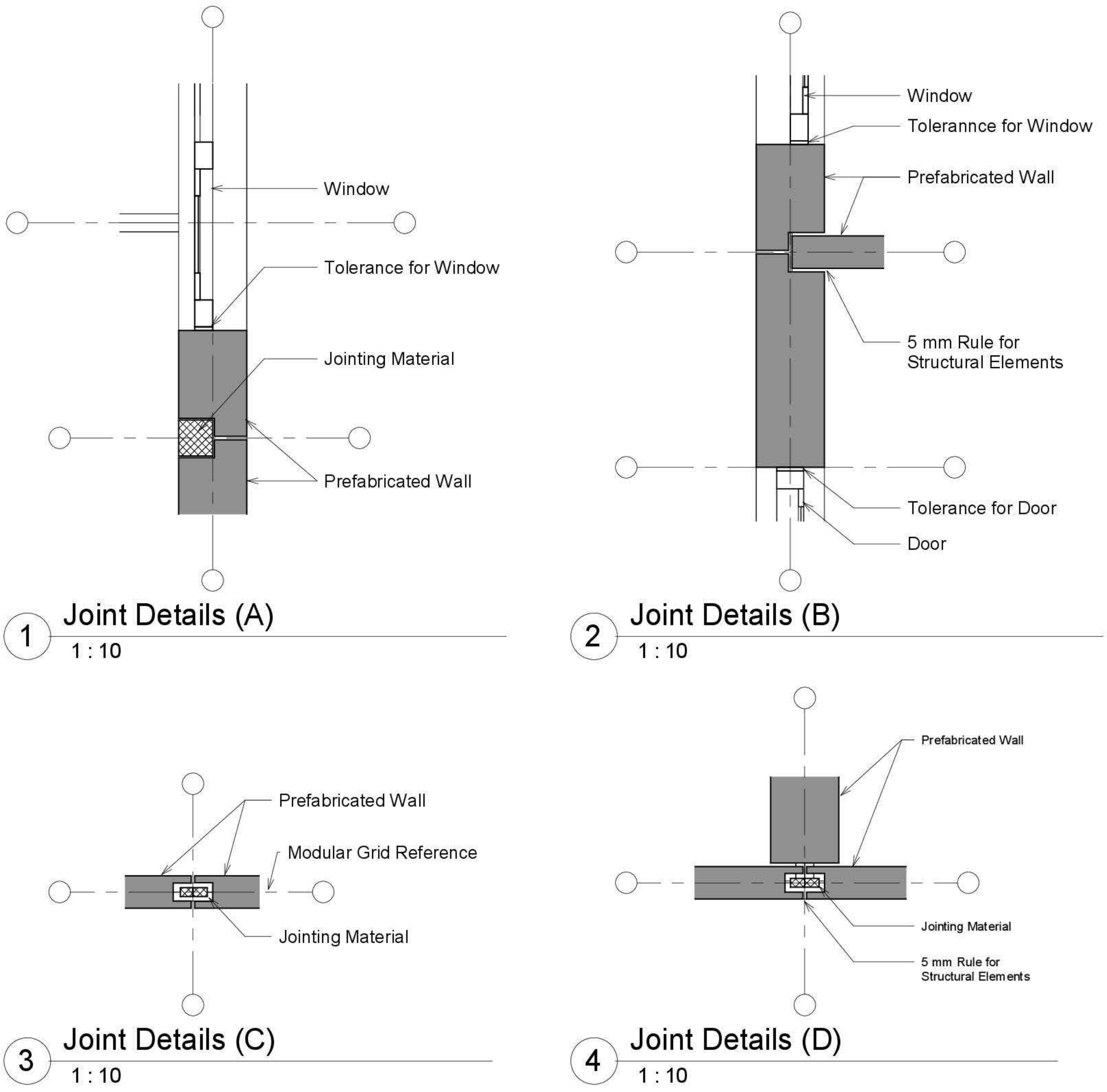

Window
Tolerance for Window
Jointing Material
Prefabricated Wall
1
Joint Details (A)
1 : 10
Window
Tolerannce for Window
Prefabricated Wall
5 mm Rule for Structural Elements
Tolerance for Door
Door
2
Joint Details (B)
1 : 10
Prefabricated Wall
Modular Grid Reference
Jointing Material
3
Joint Details (C)
1 : 10
Prefabricated Wall
Jointing Material
5 mm Rule for Structural Elements
4
Joint Details (D)
1 : 10

Figure 13

Click here to download Figure Figure 13.pdf

Figure 14

Prefabricated Elements (Slab Panels)

Type	Length	Width	Height	Thickness	Count	Cost	Mark	URL	Manufacturer	Opening Description	Description
Concrete Slab Panel - CSP-101											
3600 x 1200 x 200	3600	1200		200	16	25.00	CSP-101	http://a360.co/1eA7nBW	Concrete Works	No Opening	Corner Panel
Concrete Slab Panel - CSP-102											
3600 x 1200 x 200	3600	1200		200	2	25.00	CSP-102	http://a360.co/1eA7u0B	Concrete Works	No Opening	Corner Panel - Roof Level
Concrete Slab Panel - CSP-103											
3600 x 3000 x 200_400 x 500(1)	3600	3000		200	1	43.00	CSP-103 (1)	http://a360.co/1eA7zBd	Concrete Work	Duct Opening (400 x 500)	Corner Panel - Ground Floor - One End Joint
3600 x 3000 x 200_400 x 500(2)	3600	3000		200	1	43.00	CSP-103 (2)	http://a360.co/1eA7zBd	Concrete Work	Duct Opening (400 x 500)	Corner Panel - Ground Floor - One End Joint
4800 x 3000 x [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
4800 x 3000 x [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
4900 x 3000 x [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
4900 x 3000 x [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Concrete Slab [illegible]											
3600 x 6000 x 200	3600	6000		200	8	58.00	CSP-104	http://a360.co/1eA7iOP	Concrete Works	Staircase Opening (3900 x 1000)	Staircase Panel with Opening
Concrete Slab Panel - CSP-105											
3600 x 1200 x 200	3600	1200		200	105	25.00	CSP-105 (1)	http://a360.co/1eA79uD	Concrete Work	No Opening	Intermediate Panels
4800 x 600 x 200	4800	600		200	4	25.00	CSP-105 (2)	http://a360.co/1eA79uD	Concrete Work	No Opening	Intermediate Panels
Concrete Slab Panel - CSP-106											
3600 x 600 x 200	3600	600		200	1	22.00	CSP-106 (1)	http://a360.co/1eA6Wb1	Concrete Work	No Opening	Intermediate Panel - Roof Level
3600 x 1200 x 200	3600	1200		200	10	22.00	CSP-106 (2)	http://a360.co/1eA6Wb1	Concrete Work	No Opening	Intermediate Panel - Roof Level

Type	Length	Width	Height	Thickness	Count	Cost

Figure 15

Click here to download Figure Figure 15.pdf

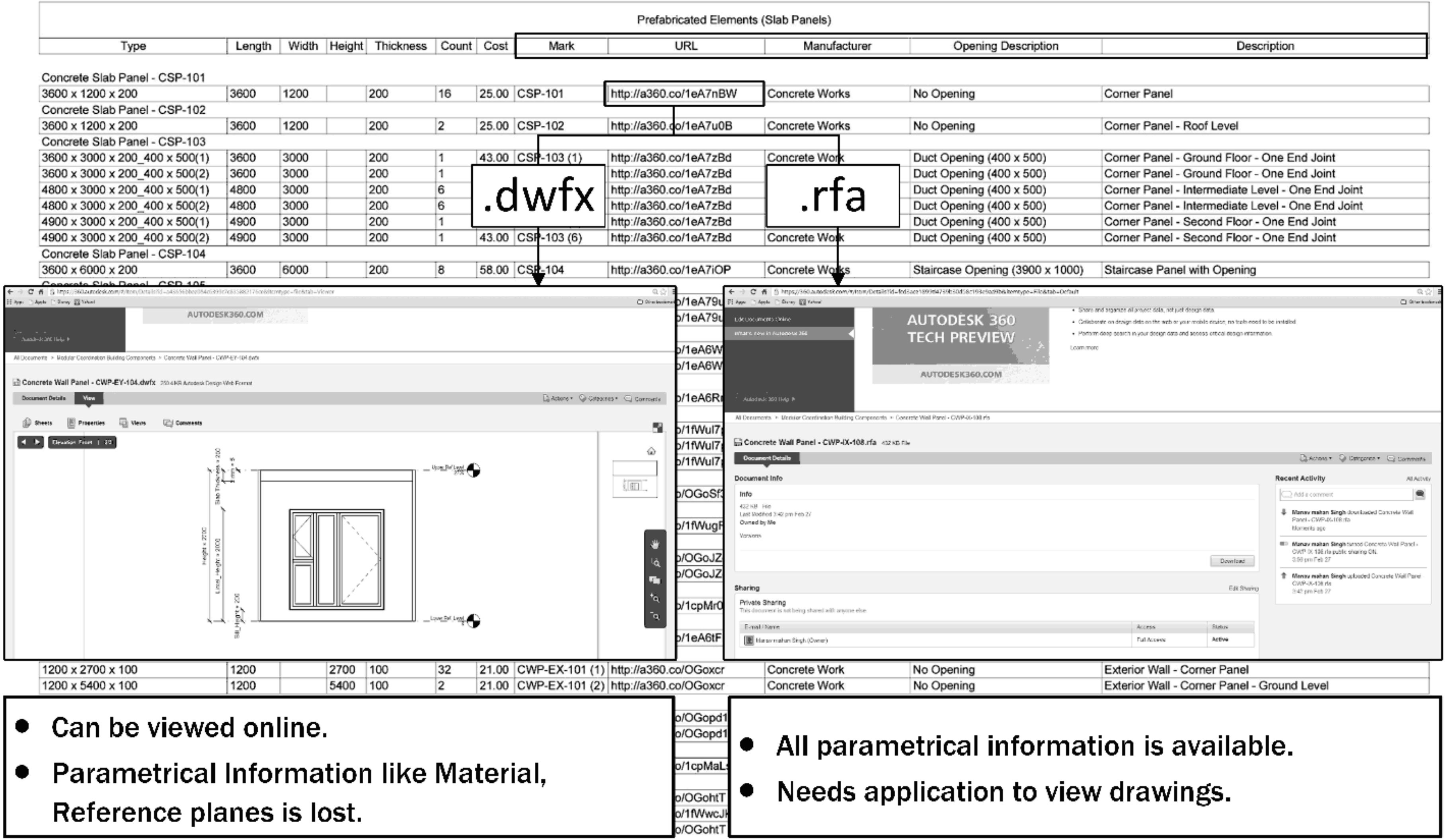


Figure 16

	User	Time Spent in Modelling	Ease of Modelling	Implementation of Modular Coordination Rules	Modelling Errors/ Mistakes	Ease in Generating Drawings/ Details	Ease in Generating Quanity Schedule	Overall Model Quality
Using tradional approach	Traditional User	2:08:00	3	1	1	1	1	2
Using the proposed framework	User 1	0:42:04	4	5		5	5	5
	User 2	0:35:00	5	5	5	5	5	5
	User 3	0:45:00	4	4	3	5	5	4
	User 4	0:54:00	4	5	5	4	5	5
	User 5	0:50:00	4	4	4	5	5	5
	User 6	0:52:00	5	5	5	5	5	5
	User 7	0:37:00	4	3	3	5	5	4
	User 8	0:20:00	5	5	5	5	5	5
	User 9	0:25:00	5	5	5	5	5	5
	User 10	0:40:00	4	4	5	5	5	5
	Average	0:40:00	4.4	4.5	4.4	4.9	5.0	4.8

Notes: 1 = Very Low/ Very Difficult; 2 = Low/ Difficult; 3 = Normal; 4 = High/ Easy; 5 = Very High/ Very Easy