Parametric Building Information Generation for Design and Construction

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Abstract

This paper demonstrates a process by which BIM models are generated from an aggregation of functions that compute relationships between constituent parts. In doing so, this process generates a modern construction model which is fundamentally rooted in synthesizing streams of information into a set of useable outputs. This process differs fundamentally from conventional parametric BIM modeling, which relies mostly on the manual placement of building elements in the context of either a large, or otherwise isolated 3D model. A specific process of team-based functional modeling is presented for creating an adaptable BIM model to preserve and generate design and construction data throughout the process, from early design stages through fabrication, assembly, and construction. A case study of Zaha Hadid Architect's City of Dreams Casino Hotel in Macau demonstrates the use of this process in a complex, real world application.

1 Introduction

The strategy for the incremental adoption of new information technologies into the industry of the built environment is as varied as the number of organizations engaged in the challenge. One of the aspects associated with the adoption of technology-led processes and workflows is the steadily increasing influence of *automation*. Slowly but surely, tasks traditionally performed by human beings are being assigned to machines. As technologies progressively mature, they begin to accommodate variation. "Mass customization"[2] in other industries brings enhanced control over product offerings to the consumer or user.

Increasingly, the emphasis on tool-making and the effective management of large degrees of variation is becoming central to design. Parametric information technologies used today in the industry of the built environment are able to combine the power of managing variation on a scale that is impossible for the individual human being to perform – with the capacity to store, access, manage and meaningfully recombine vast quantities of relevant *knowledge*.

This brings into focus the importance of the establishment of *rules* that govern the strategies to achieve desired outcomes. This infrastructure for decision making can apply to an infinite set of logical tasks, but ultimately removes the actual event or "act" of final authorship action from the hands of people, and thereby enables an accelerated execution of intent in keeping with the speed of the machine.

Evidence of the emergence of the power of the machine to enhance design and innovation is obvious in the processes, models and drawings that are the subject of this paper. Under the subject heading of "Emerging models of digital representation and fabrication," this paper documents a process that demonstrates the representative magnitude and sophistication of machine-enabled parametric design information management that is in use today.

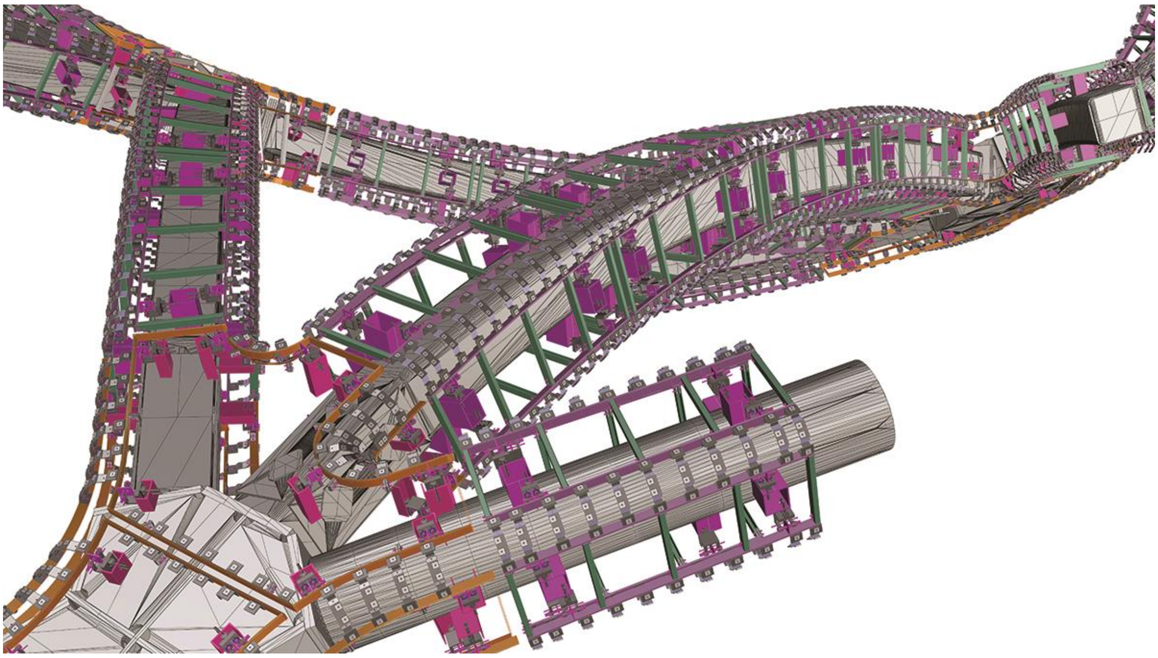


Figure 1. Illustrates the order of magnitude of scale and complexity of Building Information, generated automatically in this case study (used courtesy of the authors with permission)

2 BIG

A BIM model is the culmination of a set of processes that serves to create a representative data superset of building components used for fabrication and construction. Building Information Generation (BIG) is the framework of logic discussed in this paper to collect, combine, and give meaning to information generated in the design process and thereby give rise to a BIM model. Traditional BIM models, while great improvements over conventional representative geometry, only describe a specific state of the model, preserving little or none of the logic that was incorporated from previous states nor necessarily providing a platform for extension of the generation logic, limiting the utility of the data described by the model. BIG extends the scope of BIM and creates an adaptable BIM model that preserves and generates design and construction data throughout the design process, with each version of the model -- both data and the logic used to synthesize the data -- preserved and available throughout the design and documentation process.

The primary means by which BIG is achieved is by creating 3d models that contain lightweight representation geometry. These models are commonly referred to as wireframe models. These wireframe models are augmented with building and construction information. Wireframe models are incrementally developed into more detailed 3d models with all existing information preserved and migrated from one model to another. Ultimately the generated models can be organized and structured into various types of output to suit whatever process of transitioning the information from the digital to the physical world that is needed.

3 BIG methodology

The heart of BIG is the ability to store information in a way that is logically and functionally connected with related geometry. This information is organized as attributes. Each entry has a *key* (name of attribute) and a *value* (variable associated with the key). There are many ways to achieve this. For instance:

- Maintain a text file in parallel to the geometry
- Maintain a spreadsheet in parallel to the geometry
- Maintain a database in parallel to the geometry
- Store information directly inside the geometry

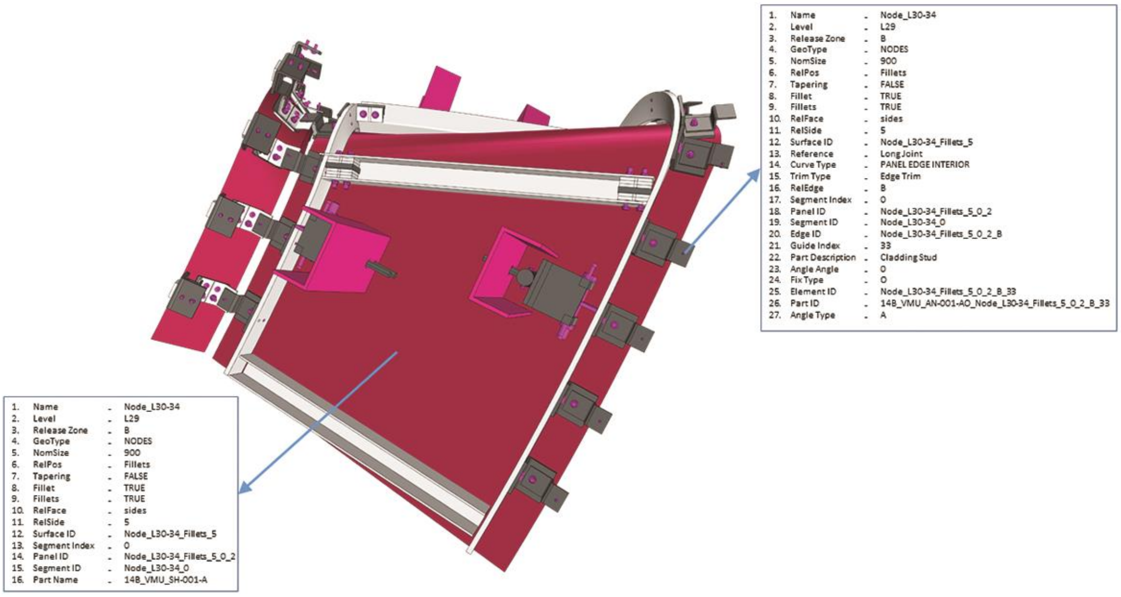


Figure 2. Each Piece of geometry is enriched with sets of data

These attributes are used to enhance future processes as well as for quantification and qualification of the generated geometry. Attributes themselves are certainly not a novel concept of BIM and in fact are core to any BIM model. In the BIG framework, attributes have dual roles for describing the geometry and also providing meaningful relationships between models in the project ecosystem.

The process of BIG, and therefore the subject of this paper, could be considered independent from the applied method. However, all examples provided in this paper have been created using Rhinoceros 3D with Grasshopper with an in-house developed add-on to Grasshopper called “Elefront” to extend the capabilities of off the shelf software to incorporate the BIG framework in a standardized manner company wide.

BIG is a process of logics to develop a design to a useful end point. The modeling process is staged and processed as a series of functions with inputs and outputs. When geometry is properly attributed, models can be combined and the attributes can be used to filter, reference, sort, and order the geometry in order to be able to perform the next sequence of functions on the geometry. The process of creating models that use information from combined results of previously generated models, is called *staging*. At each stage the previous input and generating logic is preserved and available for other stages in the project ecosystem (Figure 3). Each stage creates a model that meets a specific requirement.

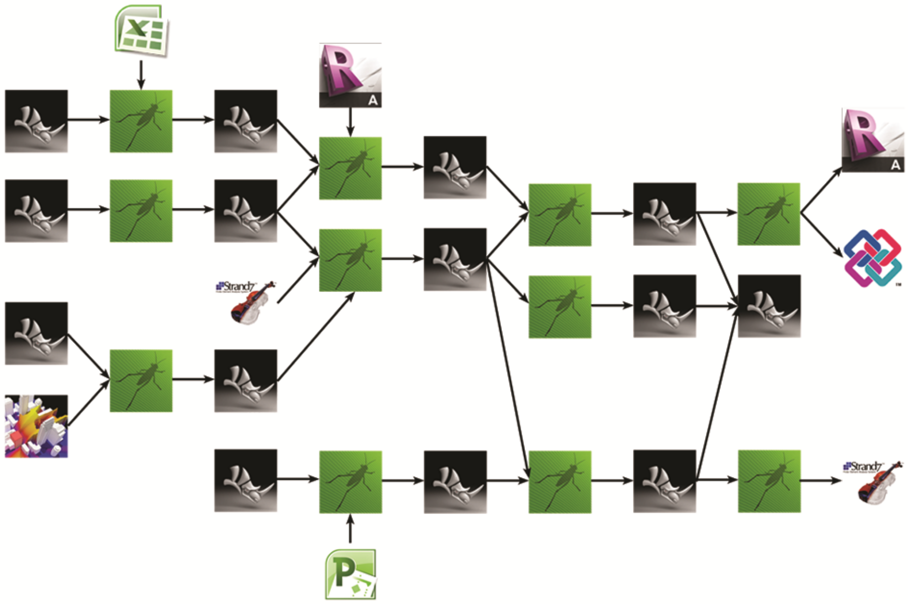


Figure 3 project ecosystem of staged models and generating logic (used courtesy of the authors with permission)

Since referencing of geometry from previous models is based on attributes, the relationships between models of each stage is explicitly defined and will remain intact even if the previous models are updated. This functionality is a fundamental enabler of the power of collaborative design, because it makes possible the distribution of tasks to more than one person.[4] This collaborative environment fosters the discretization of logics and models which serves to decrease the size and complexity of any particular model or logic. This allows for less complex logics which can be more easily managed by a person, smaller files that can be processed much faster than a single large file, and the outcomes of each stage can be used as inputs for different processes and analysis. A change anywhere in the process can be propagated by re-running the subsequent stages.

3.1 Inputs

Inputs are sets of structured data that are processed by functions to generate output. As the driving force behind the BIG process is information, it does not necessarily depend on conventions such as file formats, software or versioning. Inputs can take the form of a full 3d model, a wireframe model, a drawing, but also a spreadsheet, a diagram or a database.

Models are not created in a void. Typically design teams receive models and spreadsheets, along with diagrams and drawings to describe a building's design intent. The first step is to combine all information available into 3d models where each piece of geometry is augmented with as much information as is available at that given time. This is done by overlaying the models and diagrams, and integrating any other available databases and subsequently project information from one model to the other (Figure 4).

This process is called *data mapping* and it is the first step towards information generation.

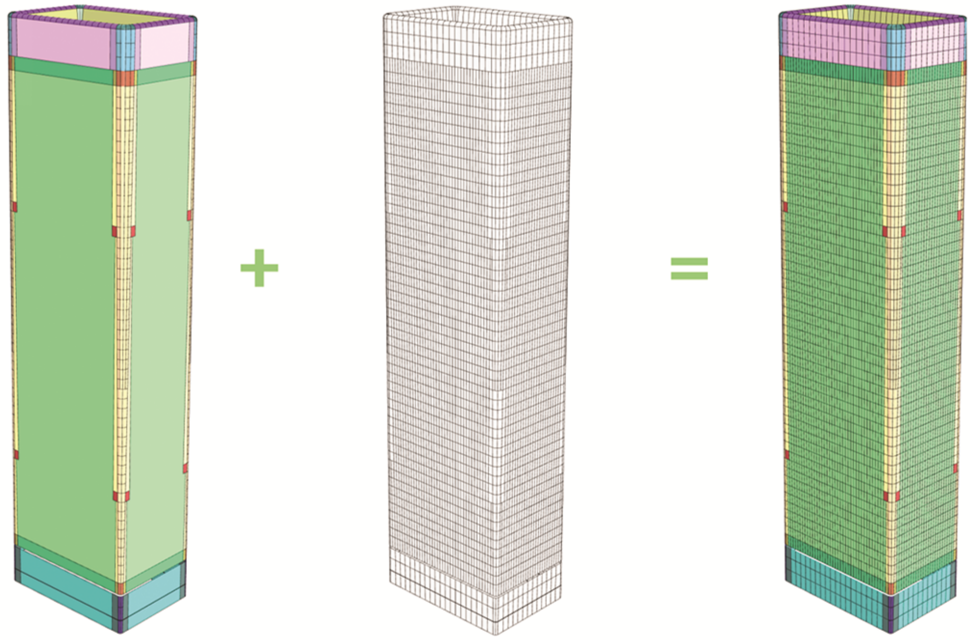


Figure 4. Illustrates overlaying of provided sets of data to create an enhanced model (used courtesy of the authors with permission)

3.2 Functions

In the context of BIG, an adaptable BIM model is a model that has the ability to respond to changes. Changes in the context of the model will have an impact on the model itself. The process being described is based on an aggregation of functions rather than the construction of a model. These functions interpret the context of the model (inputs), process these and translate them into useable results (outputs). These outputs, together with the outputs of other functions, can be used as inputs for new functions. This way, a model is no longer constructed, but it is *generated* based on the outputs of many functions.

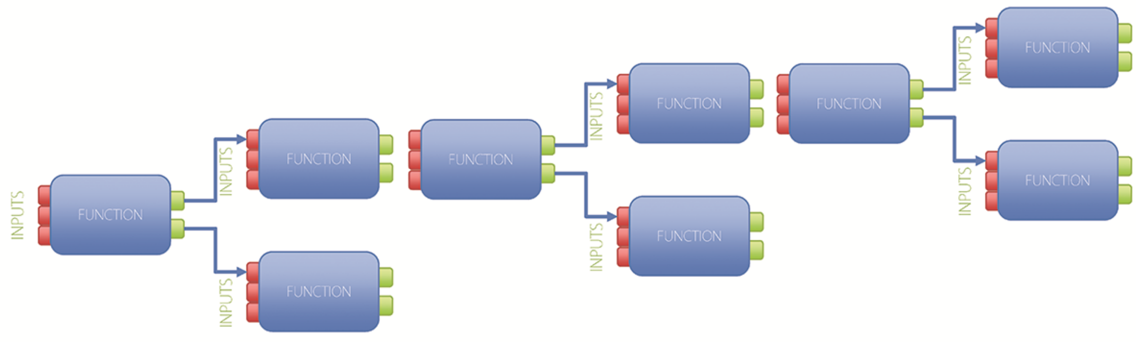


Figure 5. Illustrates the data flow through functions in parametric design (used courtesy of the authors with permission)

This concept of parametric modeling is not in itself a novelty. Platforms such as Pro/ENGINEER, Catia and Solidworks, and more recently Autodesk Revit and Rhinoceros combined with Grasshopper offer some form of parametric modeling. What differentiates BIG from these conventional parametric model building platforms, is the ability to process information in a similar way that the geometry itself is processed. Using BIG, when generating geometry, information is generated along with it and saved inside the corresponding geometry. The type of information does not have to be pre-specified, but can be assigned where needed. Similarly, the type of a building component does not need to be pre-specified and can be assigned or modified on the fly via attributing the geometry. As a result, the geometry becomes intelligent through relationships implicitly defined through information and not necessarily the physical representation of the geometry and the role of geometry becomes subordinate to the role of information. The result is that representative geometry can become less complicated than geometry created for conventional BIM models, due to the information attributed to the geometry at any stage.

With inputs formatted properly, the information as well as the geometry can be processed through the functions that have been established. The key aspect is to process the information in parallel to the geometry. When a function is performed on two sets of geometry, a similar function should be performed on the two sets of respective information. For instance, when an envelope surface is being split by surfaces that represent each level, the resulting surfaces should inherit both the information contained by their respective level surfaces and the information contained by their respective host surfaces.

Conventional BIM platforms such as Revit and ArchiCAD, apply a similar object construction logic to their processes. A wall for instance, is defined as a reference line, a wall type and a height. However, the available attributes of a wall are predefined and cannot easily be expanded or modified. Similarly, the relationships this wall can have with other building elements is limited to what is allowed for a “Wall Object” by the software. When a wall needs to be changed into an overhead door, for example, hardly any of the attributes or relationships can be preserved.

BIG does not require elements to be instances of predefined classes. A single surface can be representing anything that is defined by a surface area. The type of the object is variable. Regardless of whether it represents for instance a wall, a curtain wall or an overhead door, the relationships it has to its surroundings will be the same. The object will remain a lightweight, attributed single surface, until more specific representations are required.

3.3 Outputs

Outputs can be thought of as the results of the functions that process the inputs at a given stage. Similarly to inputs, outputs can be formatted in any way that is needed for their purpose.

Outputs at any stage can be, but are not limited to:

- Enhanced model
- Generated drawing
- Spreadsheet/Database
- Native model
- Auxiliary file format (specialist CAM models, G-code, exchange models, etc.)
- Images/Diagrams

Similar to attributes, an isolated output on its own is of little novelty in terms of the current context of the BIM industry. However, in the BIG process each output is considered as first class data and structured to exist in the project ecosystem such that both its logic and structured data is available to the project ecosystem. This means that each generated output inherits as much of the project intelligence as the format permits and allows the newly created output to form the basis of an input for any future functions. This concept allows for any output to extend the functional reach of the BIM model.

Take, for example, drawing generation. Conceptually, the process of drawing follows a specific series of instructions, or “rules”. Each line drawn has a specific meaning as well as a specific relationship to other lines. In this way, drawing is a rule-based process. When all content is present and the relationships are known, it is clear what the drawing should contain. All that needs to happen then is to apply the rules to the content. This rule-based approach is compatible with generative modeling. The content is represented by 3d models, the relationships are determined by the design of the system and the rules can be converted into functions.

In the BIG process, a drawing is conceptualized through this rule based approach and processed through the input-function-output paradigm. This approach allows for the generation of documentation data (a drawing) of an infinite number of unique objects, but also enables the documentation data to preserve the logic of the generative data (the inputs) to be used beyond the visual representation of the object.

4 Case Study and Execution

The process of BIG as described herein has been implemented on several projects throughout the authors’ firm. BIG can be applied to all phases of the design process and to many types of projects. However, due to its ability to deal with enormous amounts of data, BIG is often most beneficial when used on projects that deal with large sets of data, such as projects in the context of fabrication and construction.

The Zaha Hadid-designed City of Dreams casino project in Macau is representative of the integration of “abstraction” into the language and syntax of modern architecture. Central to the realization of abstraction in architectural language is the ability to manage and produce vast numbers of dissimilar building elements. In fact, the scale of this dissimilarity has reached the stage at which it is only possible to realize utilizing the kind of technology-enabled fabrication technology described in this paper.

The authors and their firm, working on behalf of a facade contractor, were tasked with design, engineering, modeling, and production of all fabrication documentation for 18,000m² (21,000 panels) of a double curved, 100% non-repetitive aluminum rain screen cladding system that covers the exterior primary structure exoskeleton. Due to the complexity of the various facade systems, the enclosure (glazing and exoskeleton cladding) was awarded to 4 different facade contractors and 5 different facade design teams. The authors' scope of work interfaced with all 4 of the other facade contractors' scopes. Given the complexity of interface with other parties and the sheer voluminous variability described by the design intent, a fast, adaptable process like BIG must be deployed to ensure the design intent is met under the prescribed schedule set forth by the owner.

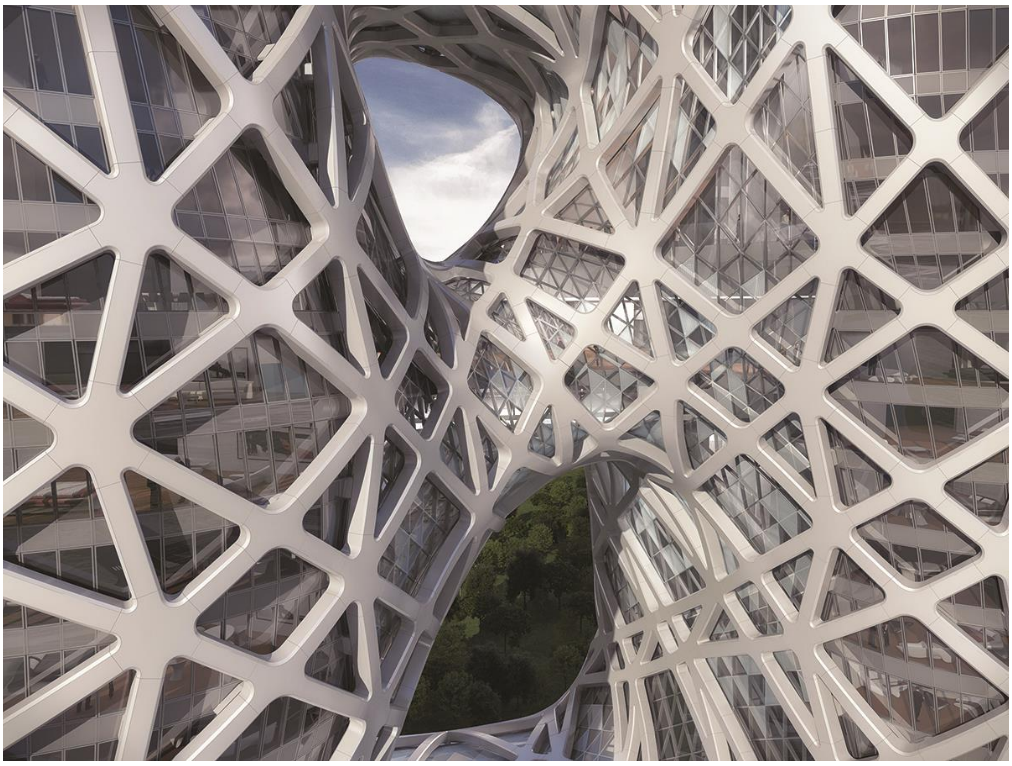


Figure 6. A portion of the authors' scope (used courtesy of Zaha Hadid Architects)

4.1 Inputs

The exterior building primary structure exoskeleton is constructed with curved steel and clad with an aluminum rainscreen and framing system. The cladding is to be fixed to the steel in the correct position and meet the required structural performance specified by the design team.

- Input 1: A spreadsheet describing the names and coordinates of the structural steel nodes

- Input 2: A wireframe model of the structural steel
- Input 3: A surface model representing the orientation of the structural steel members
- Input 4: A spreadsheet describing the steel sections of the structural steel members
- Input 5: A surface model describing the cladding envelope
- Input 6: A solid model containing geometry that represents the structural steel at the nodes.
- Input 7: Output specifications for the final product
- Input 8: Fabrication limitations

4.2 Functions

4.2.1 Structure

1. Using Input-1 a 3d model is generated containing points that are named accordingly. (Figure 7)
2. Combining this model with Input-2, the start and end points of each wire are found, and the wires attributed accordingly. (Figure 8)
3. The information about these wires is then mapped onto the surfaces from Input-3. (Figure 9)
4. Combining these models with Input-4 a solid 3d model of all the structural steel members is generated with relationships explicitly defined between the models. (Figure 10)

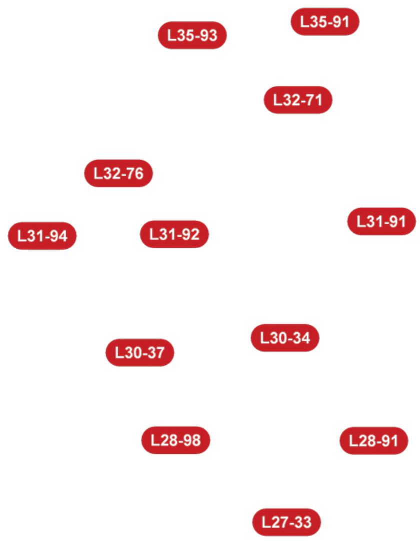


Figure 7. Node points named in model (used courtesy of the authors with permission)

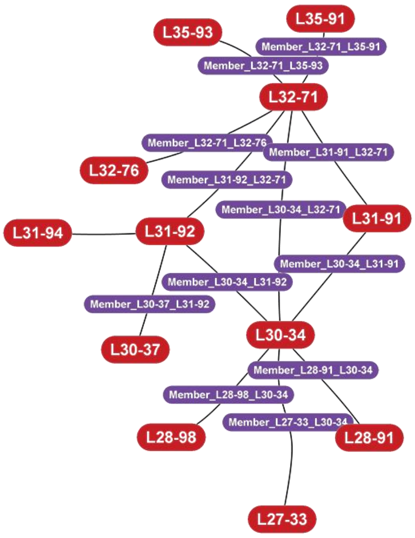


Figure 8. Wires are mapped to named nodes and attributed accordingly (used courtesy of the authors with permission)

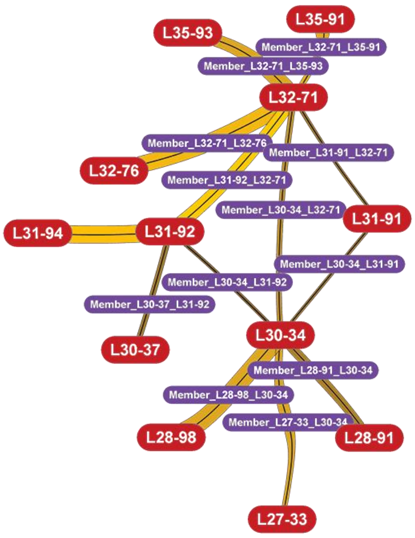


Figure 9. Supplied orientation surfaces inherit wire attributes (used courtesy of the authors with permission)

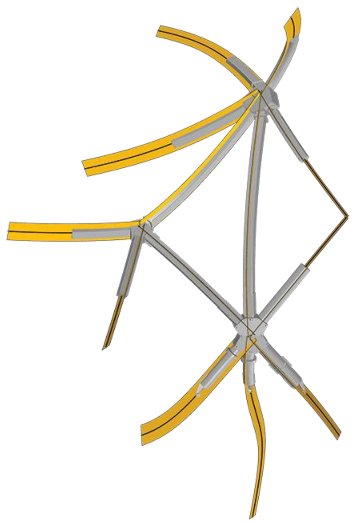


Figure 10. Fully attributed solid structural steel model is generated form wireframe data (used courtesy of the authors with permission)

4.2.2 Envelope

The envelope surface model describes the idealized shape and position of the exoskeleton cladding. All panels are directly connected and do not yet account for real world phenomena such as fabrication tolerances, installation tolerances, structural movements, thermal expansion etc.

When taking a perpendicular section through any point on a member, one can distinguish 8 different surfaces (Figure 11).

- 1 x Front surface
- 1 x Back surface
- 2 x Side surface
- 4 x Chamfer surface

Each of these surfaces need a unique identifier to locate them in the model as well as provide a logical container for the panel's framing components.

1. The attributed surfaces from Input-3 allow for the identification of the relative position of each surface that makes up a member. These surfaces also inherit the attributes from the attributed surfaces from Input-3 (Figure 11 to 13).
2. The chamfer surfaces are identified by their proximity to both front/back as well as side1/side2

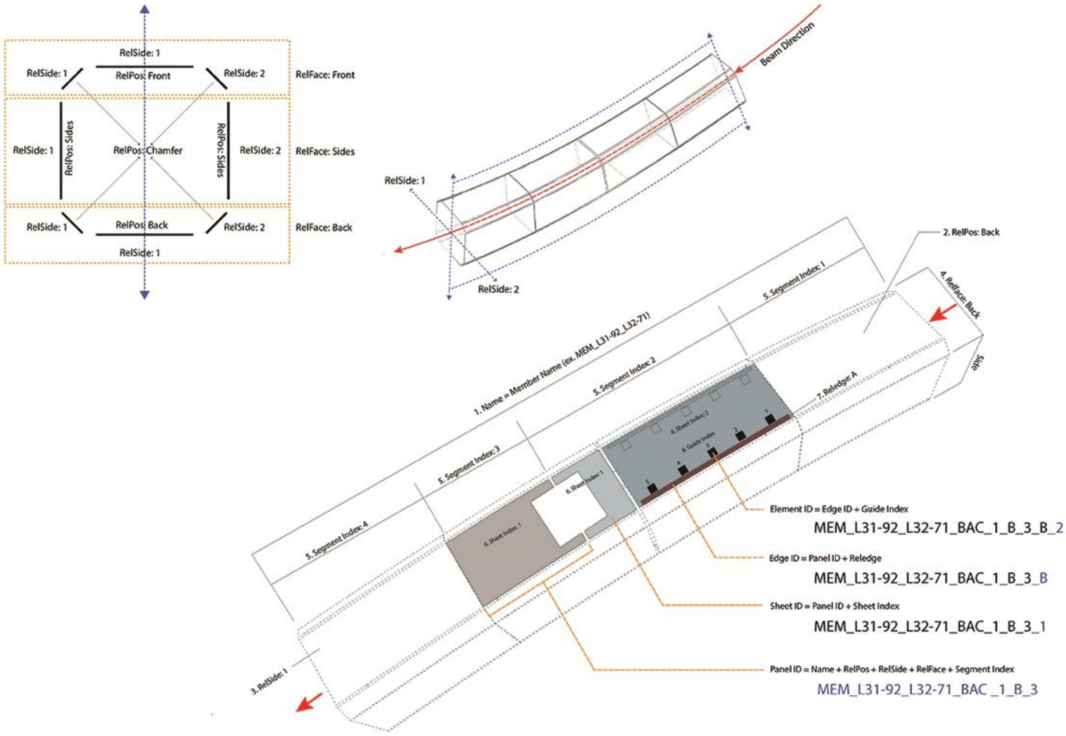


Figure 11. Identification of all possible relative positions on a member (used courtesy of the authors with permission)

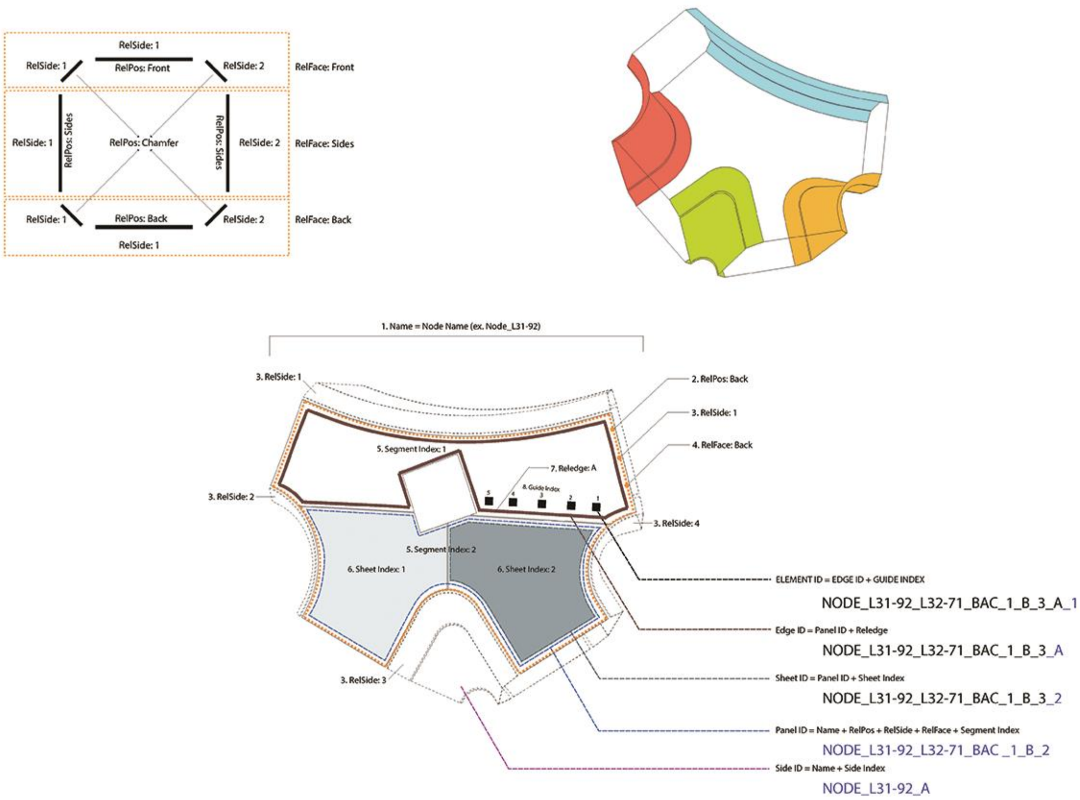


Figure 12. Identification of all possible relative positions on a node (used courtesy of the authors with permission)

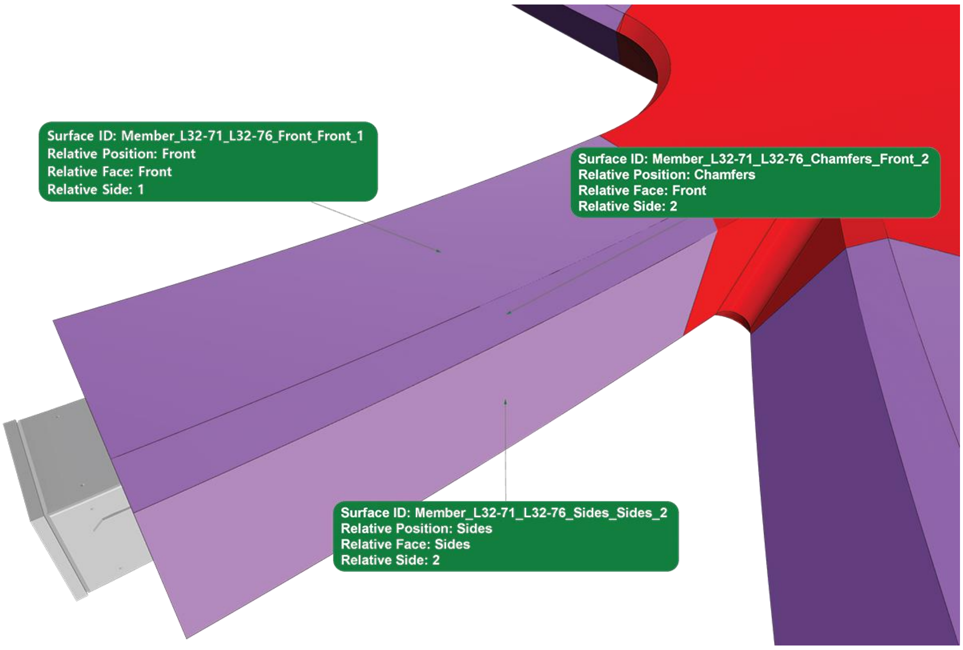


Figure 13. Panels are named according to their relative positions (used courtesy of the authors with permission)

4.2.3 Panels

Modern technologies make possible the production of building elements using highly accurate automated digital direct-to-fabrication methods. The Zaha Hadid-designed Dongdaemun Design Plaza in Korea is an example of a project that has been delivered in this way[1] However, often external factors necessitate the adoption of one or several strategies that are antithetical to the means and methods of best directly conveying the physical manifestation of an object. Material selections, engineering demands, and aesthetic requirements typically define constraints for processes available to fabricate and construct a building.[5]

For example, advanced CNC machines are often limited in capacity to both process elements in large quantities and are often restricted in the size of elements they are able to process. In the case of City of Dreams, requirements for engineering (the aluminum alloy required), panel sizing, and assembly processes eliminated the use of CNC forming machines for the majority of the infinitely variable, double curved aluminum panels. Furthermore, often political and economic constraints direct a project to seek solutions under specific geographic regions.

The design and documentation process must be able to accommodate a graceful degradation of 1-to-1 translation of the digital to physical, allowing an object to be described equally well on paper as it is in a pure 3d environment. The design and documentation process must also be able to support a one-to-many relationship between an object and a means of conveyance as due to imposed constraints. For example, for any object, one or many means of fabrication (and as many different fabricators) may be employed to create those objects but not allowing those objects to differ visually as described by the design intent.

The fabrication of the panels for the City of Dreams is no exception. Given the large panel size requirements set forth by the design intent (2m x 5m) as well as the vastly different shapes and curvatures in the panels, a variety of manual and CNC forming processes are employed to a) comply with fabrication limitations, b) meet budget requirements, and c) ensure the production schedule can be met. This configuration begets the following organizing problems:

- Panels need to be identified correctly according to forming process
- Documentation data needs to be generated for each process
- The panels need to be tracked through the fabrication process and appropriate QA/QC data is to be generated to check the fidelity of the constructed product

Figure 14. A post formed CNC cut panel, one part of one of the methods used to fabricate the exterior cladding panels

The first step to solve these organizing problems is to determine the location of the panel joints. Joint lines are determined and then panel surfaces are trimmed (Figure 15). The resultant surfaces are then checked against prescribed fabrication constraints and attributed accordingly. The wireframe of the panel framing is generated relative to the back face of the panels, based on system rules, engineering results and the shape of the panel. Framing around penetrations need particular attention (Figure 16). System design and engineering dictate the functions that generate the hardware locations. The magenta colored hardware assemblies (Figure 17) represent the bracketry that ultimately connects to the structural steel.

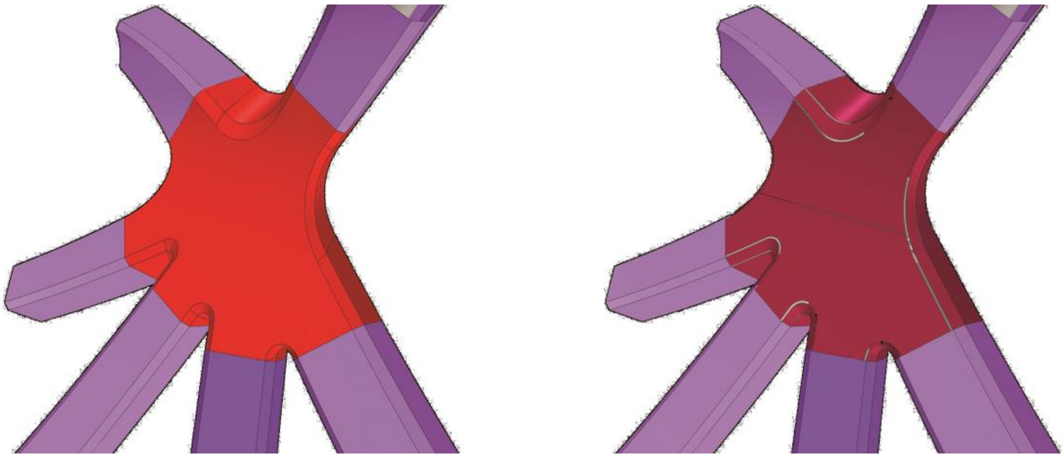


Figure 15. Simple subdivision of panel based on prescribed fabrication constraints (used courtesy of the authors with permission)

Figure 16. Generation of the location specific framing members (used courtesy of the authors with permission)

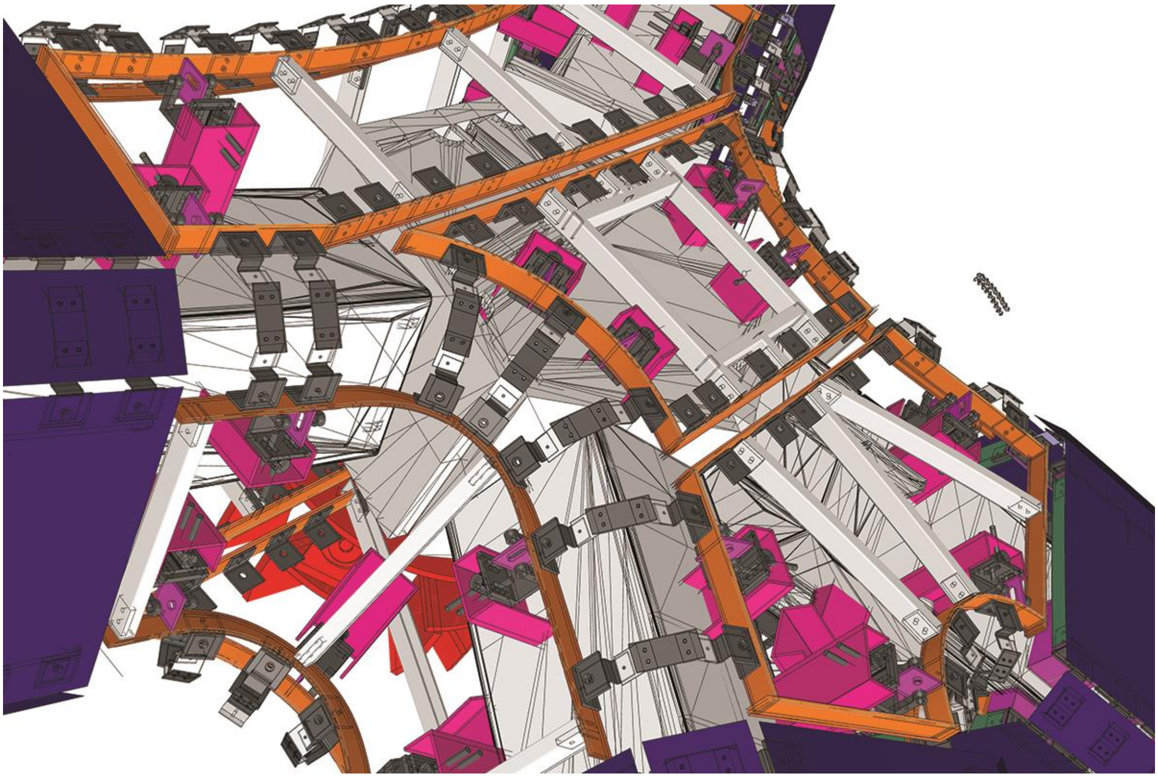


Figure 17. Panel framing hardware (used courtesy of the authors with permission)

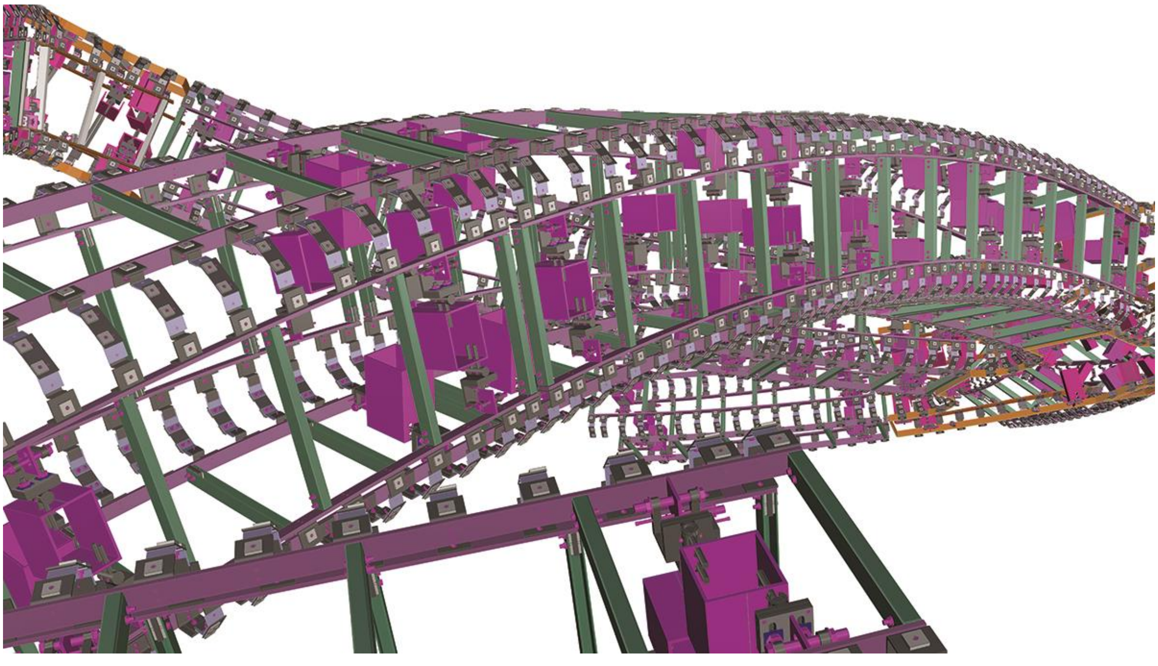


Figure 18. Completed panel framing (used courtesy of the authors with permission)

4.3 Outputs

As a wide variety of manufacturers and installers are involved in the construction of this system, there is a need for varied outputs that are tailored to each respective trade. The application of the different types of output are described below.

Due to the irregular shape of the building, most parts have a unique shape and therefore there is a need to generate many thousands of drawings. In fact, it is not uncommon for a project of this scale and complexity to require in excess of 100,000 paper drawings. The vast majority of the drawings for this project are all generated automatically and, without any human input, submitted directly for fabrication (Figures 19 and 20).

The attributed geometry allows for functions to be created to represent the modeled information as tabular data. Quantity takeoff of thousands of different items are a common output (Figure 21).

Some framing rails for the panels are double curved. The manufacturer requested 3d models in our native file format for their further action. Besides the solid geometry of the aluminum rails, reference surfaces for interior face, center line and exterior face are provided. Point objects of varying color and type are added at hole locations as well as at locations that need supporting stud welds to accompany the drawing data generated in parallel. (Figure 22).

The interface with the primary structure is an essential part of the system design and the communication of this specific piece of design information is critical. The primary means of data transfer regarding the structural interface takes place through spreadsheets for coordinate translation and a 3d model for visualization and fabrication data. 2d layout drawings are generated for cross checking the layout of the interface components in the steel shop (Figure 23 and 24).

The open BIM standard IFC is the chosen platform, as this format allows for a software agnostic information exchange. IFC has very strict specifications as to how geometry is described and these are in many ways different from the way geometry is defined in many modelers. As all our objects are explicitly defined and all components are attributed, creating an IFC model is only a matter of formatting the data into compatible streams (Figure 25).

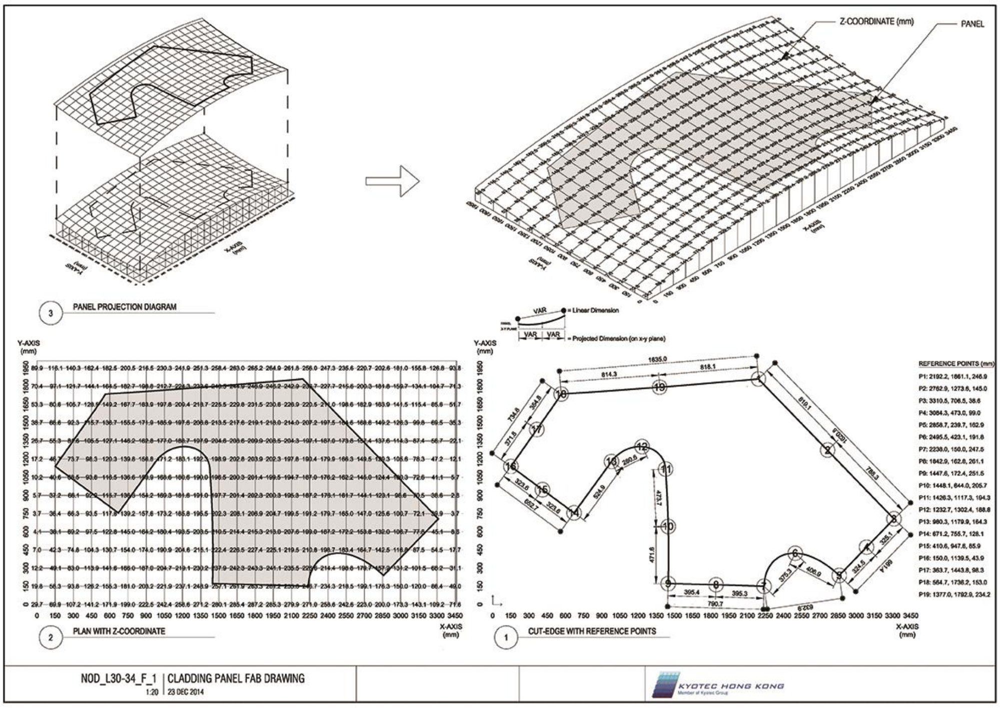


Figure 19. A typical panel fabrication drawing generated for this project that contains all of the information construct and check a panel.

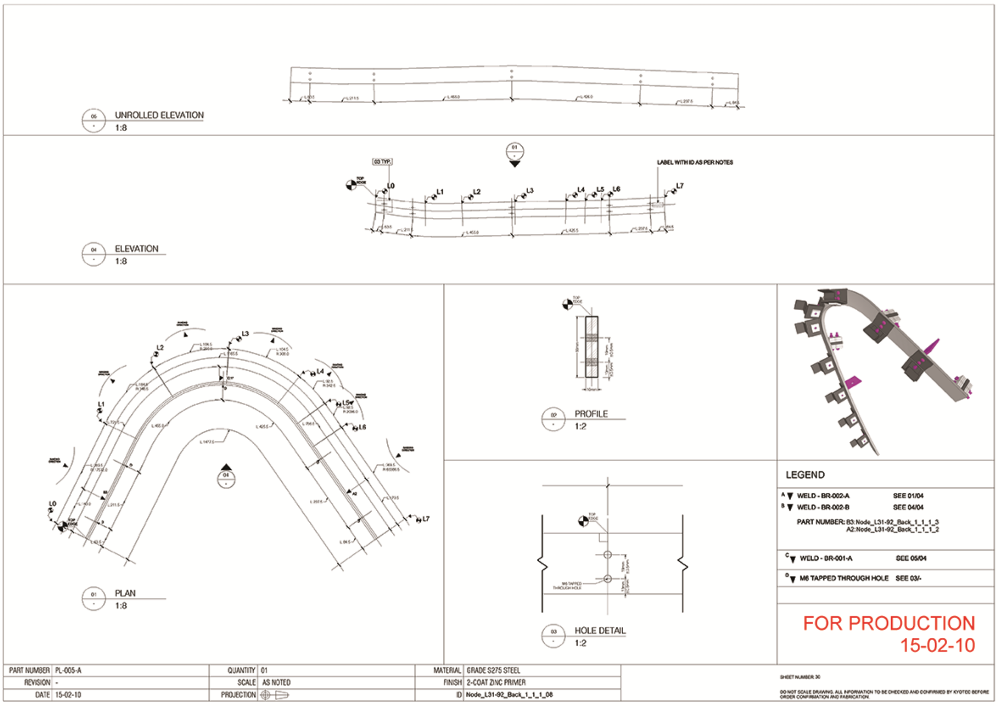
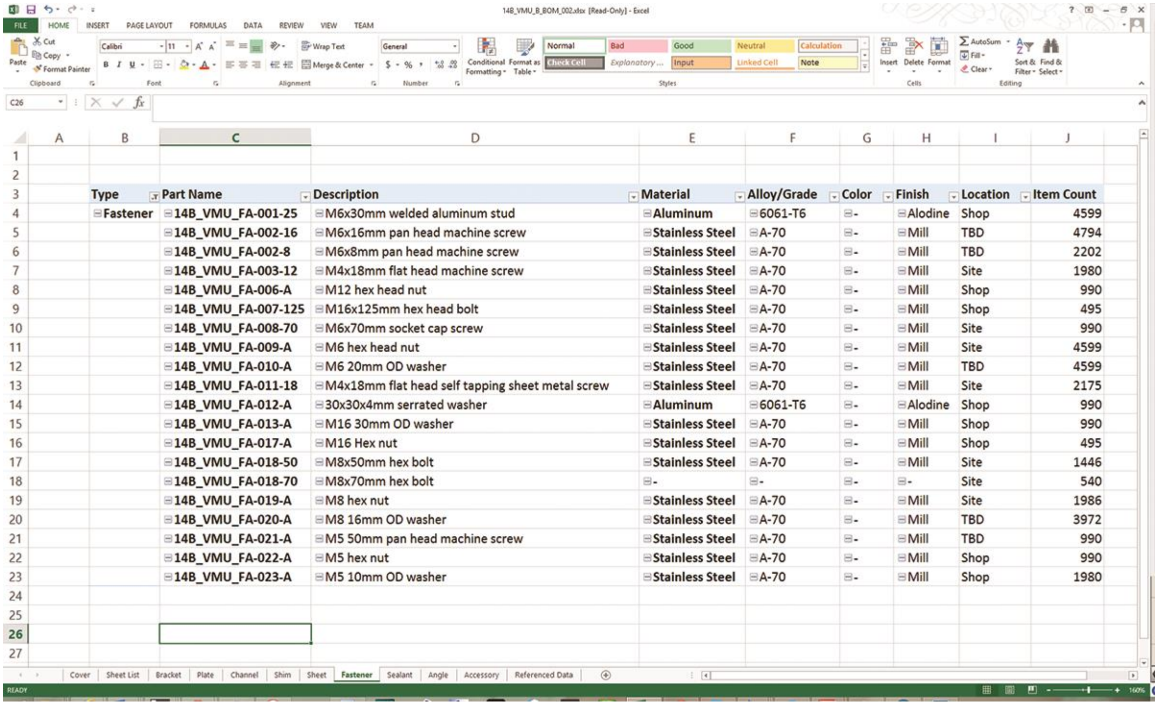


Figure 20. The panel framing elements are curved along several different radii. Accuracy of hole locations for connecting brackets is critical for panel-to-panel alignment. Dimensioning techniques like measuring along an arc are developed specifically for this task (used courtesy of the authors with permission)



Type	Part Name	Description	Material	Alloy/Grade	Color	Finish	Location	Item Count
Fastener	14B_VMU_FA-001-25	M6x30mm welded aluminum stud	Aluminum	6061-T6	-	Alodine	Shop	4599
	14B_VMU_FA-002-16	M6x16mm pan head machine screw	Stainless Steel	A-70	-	Mill	TBD	4794
	14B_VMU_FA-002-8	M6x8mm pan head machine screw	Stainless Steel	A-70	-	Mill	TBD	2202
	14B_VMU_FA-003-12	M4x18mm flat head machine screw	Stainless Steel	A-70	-	Mill	Site	1980
	14B_VMU_FA-006-A	M12 hex head nut	Stainless Steel	A-70	-	Mill	Shop	990
	14B_VMU_FA-007-125	M16x125mm hex head bolt	Stainless Steel	A-70	-	Mill	Shop	495
	14B_VMU_FA-008-70	M6x70mm socket cap screw	Stainless Steel	A-70	-	Mill	Site	990
	14B_VMU_FA-009-A	M6 hex head nut	Stainless Steel	A-70	-	Mill	Site	4599
	14B_VMU_FA-010-A	M6 20mm OD washer	Stainless Steel	A-70	-	Mill	TBD	4599
	14B_VMU_FA-011-18	M4x18mm flat head self tapping sheet metal screw	Stainless Steel	A-70	-	Mill	Site	2175
	14B_VMU_FA-012-A	30x30x4mm serrated washer	Aluminum	6061-T6	-	Alodine	Shop	990
	14B_VMU_FA-013-A	M16 30mm OD washer	Stainless Steel	A-70	-	Mill	Shop	990
	14B_VMU_FA-017-A	M16 Hex nut	Stainless Steel	A-70	-	Mill	Shop	495
	14B_VMU_FA-018-50	M8x50mm hex bolt	Stainless Steel	A-70	-	Mill	Site	1446
	14B_VMU_FA-018-70	M8x70mm hex bolt	-	-	-	-	Site	540
	14B_VMU_FA-019-A	M8 hex nut	Stainless Steel	A-70	-	Mill	Site	1986
	14B_VMU_FA-020-A	M8 16mm OD washer	Stainless Steel	A-70	-	Mill	TBD	3972
	14B_VMU_FA-021-A	M5 50mm pan head machine screw	Stainless Steel	A-70	-	Mill	TBD	990
	14B_VMU_FA-022-A	M5 hex nut	Stainless Steel	A-70	-	Mill	Shop	990
	14B_VMU_FA-023-A	M5 10mm OD washer	Stainless Steel	A-70	-	Mill	Shop	1980

Figure 21. Generated full BOM report on associated hardware (used courtesy of the authors with permission)

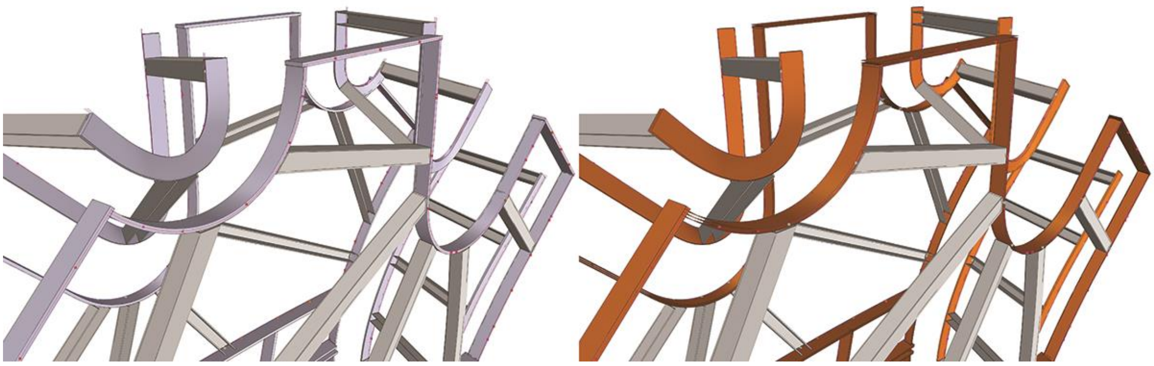


Figure 22. Double curved rail geometry before exporting to individual models (used courtesy of the authors with permission)

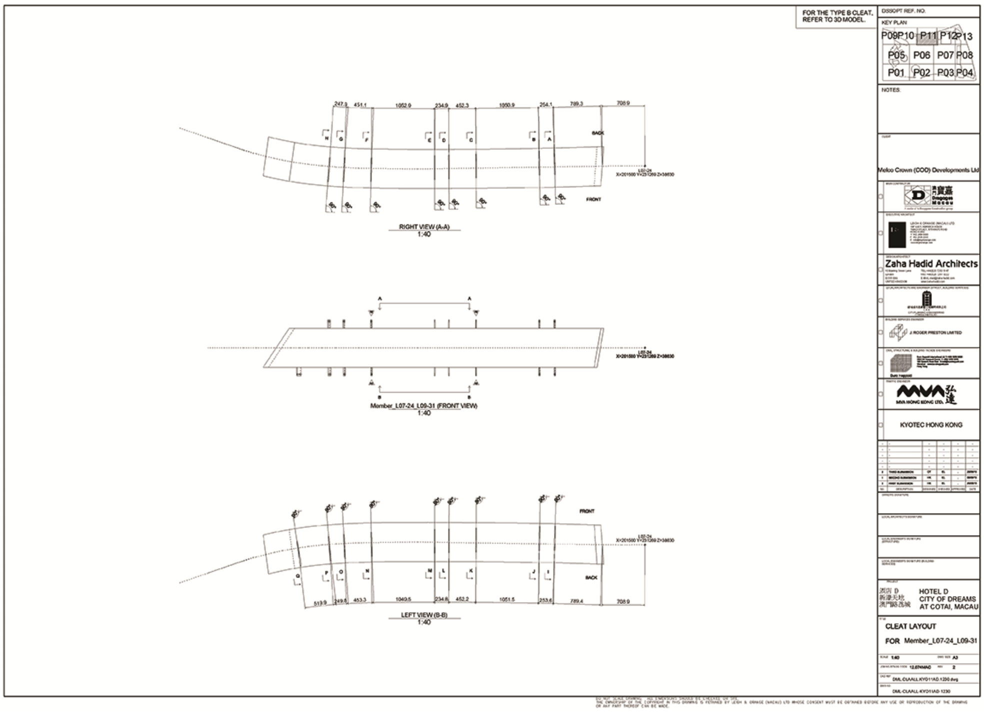


Figure 23. A generated QA/QC drawing for physical inspection of the primary structure (used courtesy of the authors with permission)

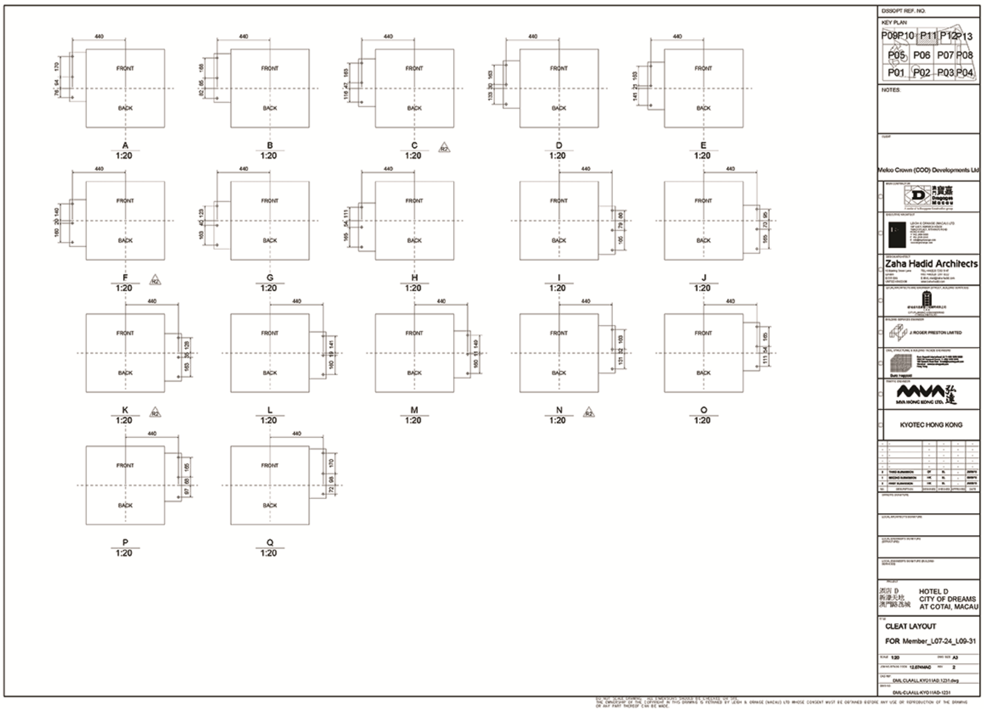


Figure 24. Each individual cleat is sectioned and dimensioned relative to the construction steel (used courtesy of the authors with permission)

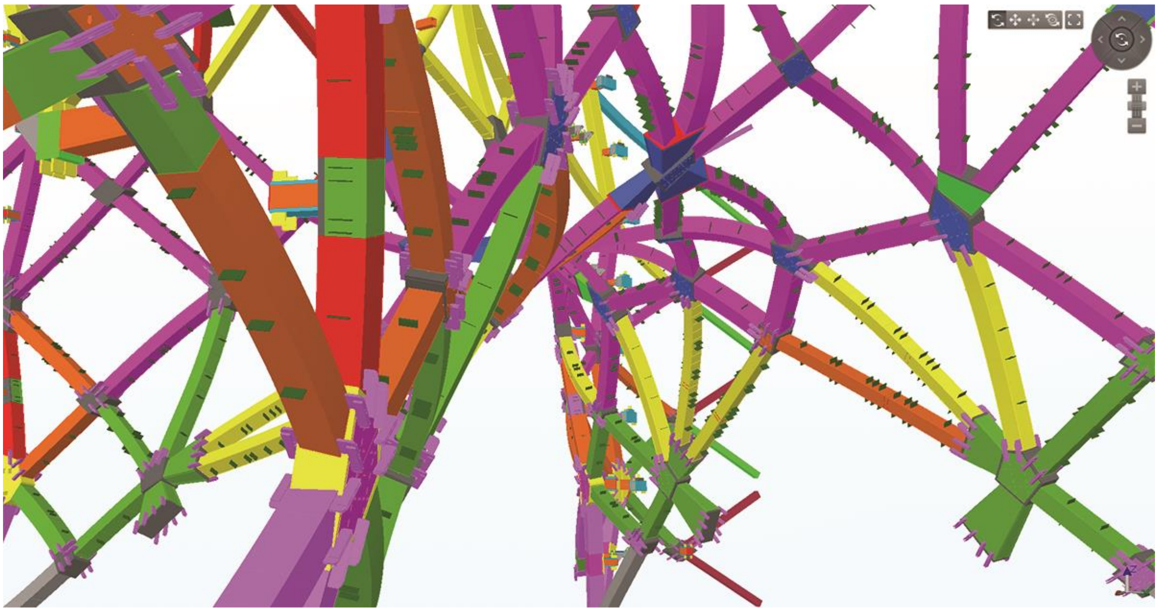


Figure 25. Coordination of generated variable cleat geometry with the steel contractors TEKLA steel model (used courtesy of the authors with permission)

5 Conclusion

A 3d model is unfit for reuse, as no two buildings are ever the same. However, the codified project intelligence and knowledge can be re-used. This case study demonstrates the advantages of structuring the processing of information very clearly and dividing these processes into generic operations that are separate from project specific operations.

Each successive project has the potential to be better than the previous one, because knowledge reuse enables project teams to focus on what can be improved. Knowledge can be incrementally added to the workflow thereby creating an intelligent process. Future research and development of this process will include creating a more collaborative and software agnostic platform. The BIG process represents an opportunity to further shift the role that designers perform in the production of design and fabrication information. The role of manually producing singular instances of 3d models is shifting to being one of "rule makers" who establish logical relationships and build team consensus about project knowledge and execution. The influence this has on design and fabrication is significant, and it echoes the potentially enormous impact on the industry as a whole. The centuries-old profession of architecture is in the process of being "encoded"[6] and - at least partially - being entrusted to machines, with all of the workflow restructuring and culture changes that this entails.


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Figure 26. Completed visual mockup for City of Dreams (used courtesy of the authors with permission)

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