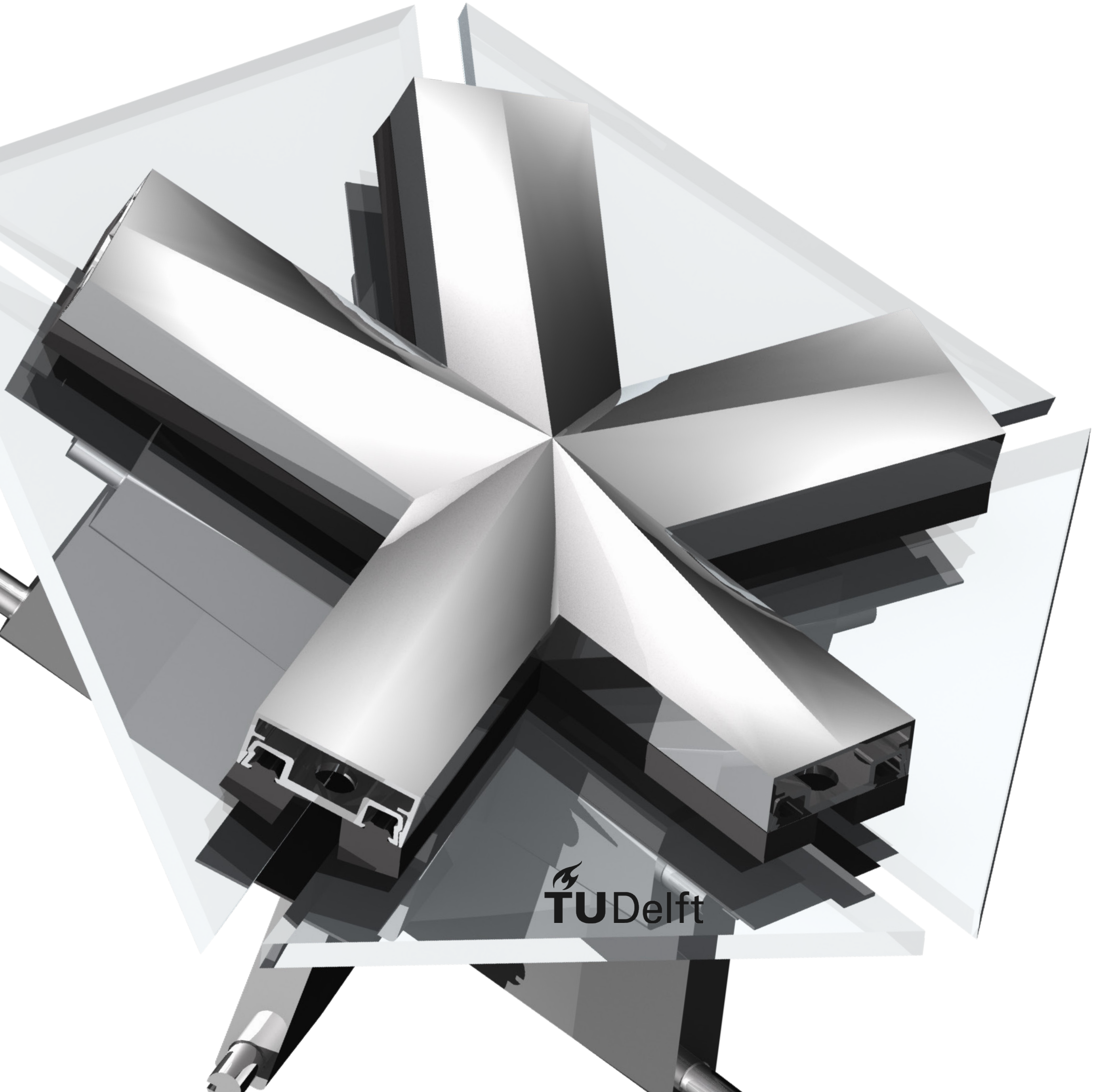
Nodable

By Lia Tramontini

An Additive Manufacturing Solution for Free-Form Steel Curtain Walls.



TU Delft

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00
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01
Introduction

The main function of the building envelope consists of providing a physical barrier between the conditioned and unconditioned environment, including, but not limited to, control of air, water, vapour, heat, sound, and light. Throughout the past several decades in particular, as the requirements for building envelopes have steadily increased, facade systems have evolved from craftsmanship oriented constructions to highly developed systems (Klein, 2013), which not only perform the practical functions required by its definition, but also contribute to the aesthetic, branding and experience of a building. The modern curtain wall in particular is a response to the desire for maximum transparency, enabled by a steady stream of innovation in construction technology. The desire for transparency has seen us evolve from mass-wall construction with very limited apertures, to the iconic structural glass entrance of the 5th Avenue Apple Store.

The energy performance requirements for building envelopes have been of growing concern in the architecture industry dating back to the 1970s oil crisis. Since then, and due in particular to the growing concern for climate change, energy regulations and incentives for sustainable development are becoming more prevalent and more stringent. As the facade is one of the most critical elements in a building's energy use, the focus on building envelopes for architectural innovation has rendered it one of the most complex and intelligent assemblies in the building - one that is able to achieve both the desired level of transparency, and required energy performance, two features which can often be in direct opposition. What was once an uncoated single-glazed facade such as that on the iconic 1952 New York City Lever House has evolved into complex assemblies that comprise elements fitted with various layers, films, insulating gases, solar control devices (fixed, operable, or dynamic), thermal breaks and other pieces to a kit of parts that enable adequate performance, as well as fabrication, installation. These elements enable the facade to provide a high performance of air, water and vapour management, while resisting structural loading, and still enabling the level of transparency that we desire in our buildings.


Image Source: ww.teamworkglass.com

The geometrical complexity of enclosures has also increased due to the rapidly increasing popularity and accessibility of parametric design tools (Strauß, 2013). Parametric Design was used in its first constructed application in the development of a stadium by Luigi Moretti as early as the 1970s (Fraser, 2016), and by a limited number of architects including Frank Gehry throughout the next four decades. In the past decade, the popularization of visual scripting programs such as grasshopper, which enable architects to develop parametric designs with an interface that requires little to no understanding of traditional coding languages, has speed-tracked the design and fabrication complex building skins, and emboldened architects to design more geometrically complex buildings.

With both sustainability initiatives and the power of parametric design taking the world of architecture by storm, facade manufacturers have been challenged with the task of adapting their enclosure systems to the rapidly increasing demands of the architecture market. While the architecture industry in this sense is very ambitious, it is also economically conservative, and therefore the validity of assemblies and components that respond to its demands are unquestionably subject to the efficacy and cost of their manufacturing and assembly.

Until now, this has meant that any innovation that took place in facade design, did so within the industrial framework established by the mass-manufacturing mindset of the second industrial revolution. The increasing capabilities and accessibility of additive manufacturing however, disrupts this mindset, as it enables, or will enable in the near future, the economical and reliable manufacturing of custom, complex elements. In an Economist article published in 2012 (Rifkin, 2012), the Third Industrial Revolution is defined as the shift from manufacturing methods that rely on economy of scales to economical individualized production due to the digitization of manufacturing. This revolution stands to conquer the limitations that traditional manufacturing imposed on innovative facade design.

This report seeks to explore the potential of additive manufacturing as a solution to enabling free-form design while improving the performance of a standard enclosure system. While similar studies have been undertaken for aluminium system, including a commercial precedent that exists in Schuco's "parametric facade", this paper seeks to explore the territory of a parametric steel facades: one that learns from the strong points and weaknesses of the existing aluminum solutions, but is adapted to steel curtain wall systems, which are noted for their strength, transparency and elegance.

In AM Envelope (Strauß, 2013), the author outlines a number necessary considerations in promoting the use of Additive Fabrication in façade construction:

► Achieve a deeper understanding of the potential and possible added value that AM offers: performance, material savings, functional constructions, marketing of the technology, optimized stock-keeping (on-demand production, just-in-time management), digital designing (freedom of geometry, technically improved joints, load-transfer optimized building parts, combination of different functions in fewer component layers);

► Understand the potential and let it flow into better constructions;

► Clarify everyone's expectations concerning the integration of the technologies into building technology, and to formulate realistic options in terms of realizing customer wishes;

These considerations serve as a good framework for this research, which aims to combine knowledge about traditional steel curtain walls and innovative additive manufacturing technology with the objective of designing an industry relevant solution or free-form curtain wall construction, in partnership with industry professionals.


SUSTAINABLE BUILDING
PERFORMANCE


HIGH TRANSPARENCY


COMPLEX GEOMETRY

1.1
Problem Statement

The increasing trend in the industry to construct high transparency building enclosures with complex geometry has challenged the facade industry to respond with innovative ways of solving the structural and performance challenges of complex building enclosures. The root of the challenge is a geometrical one, which happens in translating a free-form CAD (computer aided design) surface element into a three dimensional network of building components.

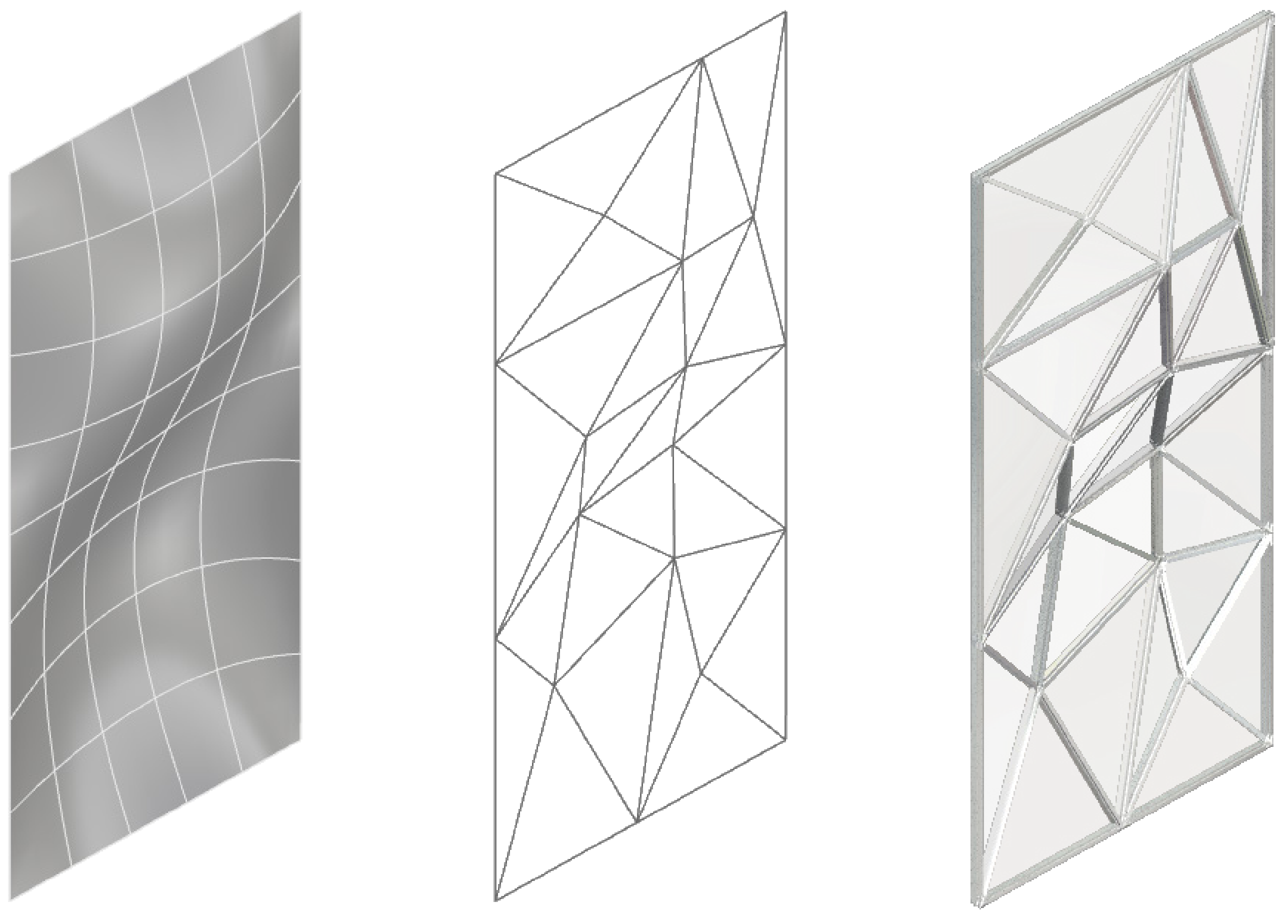
The process of creating modern free-form facade typically begins with the generation of a NURBS (Non-Uniform Rational B-Spline) surface element which is used to extract a network of curves that represent the structural framework for a reticulated a structure, meaning a structure made up of a net-like intersecting lines forming the basis for its structural network. The NURBS surface is different from algebraic surfaces in such as cylinders or spheres, which are easily definable by fixed mathematical equations, in that they are the “complex construct of mathematical objects like lines curves, and planes, formula and procedures, which interact to specify or even create a new form” (Stephan et al., 2004).

The process of extracting the curve network can be based on a number of factors, including but not limited to, desired pattern, planarity of subdivisions, dimensional limitations of subdivisions, structural behavior, and smoothness of the final geometry. The curve network extracted from the surface defines the placement of structural sections and the intersection points between curves locate the node at which these sections intersect. Structural sections generally have a polygonal profile, such as a T or I section, or a rectangular or square section, that is oriented in such a way that its main axis is in line with the bisector angle of the two adjacent planes that the section intersects. In free-form facades, “permanently changing curvature” (Stephan et al., 2004) results in a complex geometrical relationship between incoming members that is both challenging to resolve, and unique at every individual node.

As Illustrated in “Reticulated Structures on Free-Form Surfaces” (Stephan et al., 2004), the geometry of incoming members can be defined by their rotation in three angles, the horizontal angle, vertical angle, and twist angle. The horizontal angle, U, is the polar angle of the structural member on the node tangent. The vertical angle, V, is the polar angle of the structural member with the node normal. The twist angle, W, is the angle between the normal plane of the member and the plane defined by the normal and longitudinal member axis. These are illustrated in Figures 1.1.2, 1.1.3 and 1.1.4, respectively.

The variation across the facade of these measures creates a challenge in reconciling the geometry at nodes in such a way that it creates an effective scenario for load transfer, an acceptable platform for quality of air/ water/vapour control, and that it does not compromise the aesthetic of the facade. In addition, the complicated nature of free-form facade geometry is such that it is costly and labor intensive with traditional manufacturing methods. Individual solutions and complex geometry under traditional manufacturing limitations often requires manual work which increases construction tolerances and in turn potentially decreases the performance of the building enclosure. Poor workmanship and improvised solutions can often result in unwanted leakage (Strauß, 2013) that ultimately undermines the overall performance of the entire building envelope and impacts its durability (Figure 1.1.5).

Ultimately, while the digital design tools that we have available in the industry lend themselves well to complex geometry, the physical elements that we have at our disposal to construct this geometry with, which are designed for mass manufacturing, generate facades with diminished building performance and greatly increased labour intensity during fabrication and assembly, and in some cases, are incapable of being used in free-form architecture at all.



Input NURBS Surface *Reticulated Reference Geometry* *Built Components*

Figure 1.1.1: Geometry evelopment in freeform facades
Source: Author

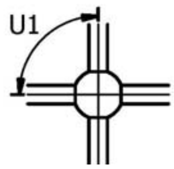


Figure 1.1.2: U Angle
Source: Stephan, Knebel & Sanchez-Alvarez, 2004

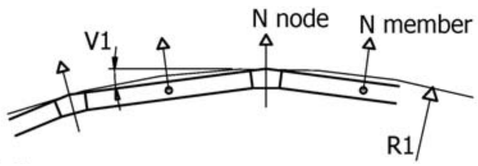


Figure 1.1.3: V Angle
Source: Stephan, Knebel & Sanchez-Alvarez, 2004

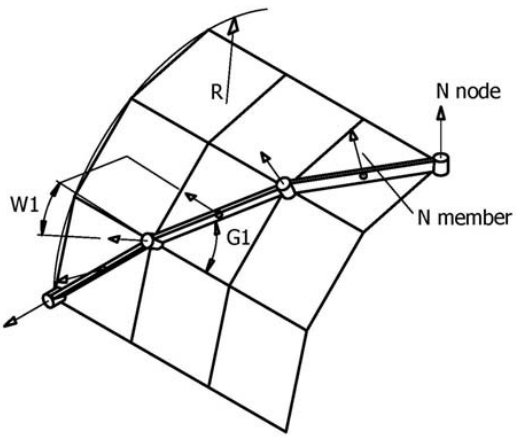


Figure 1.1.4: W Angle
Source: Stephan, Knebel & Sanchez-Alvarez, 2004

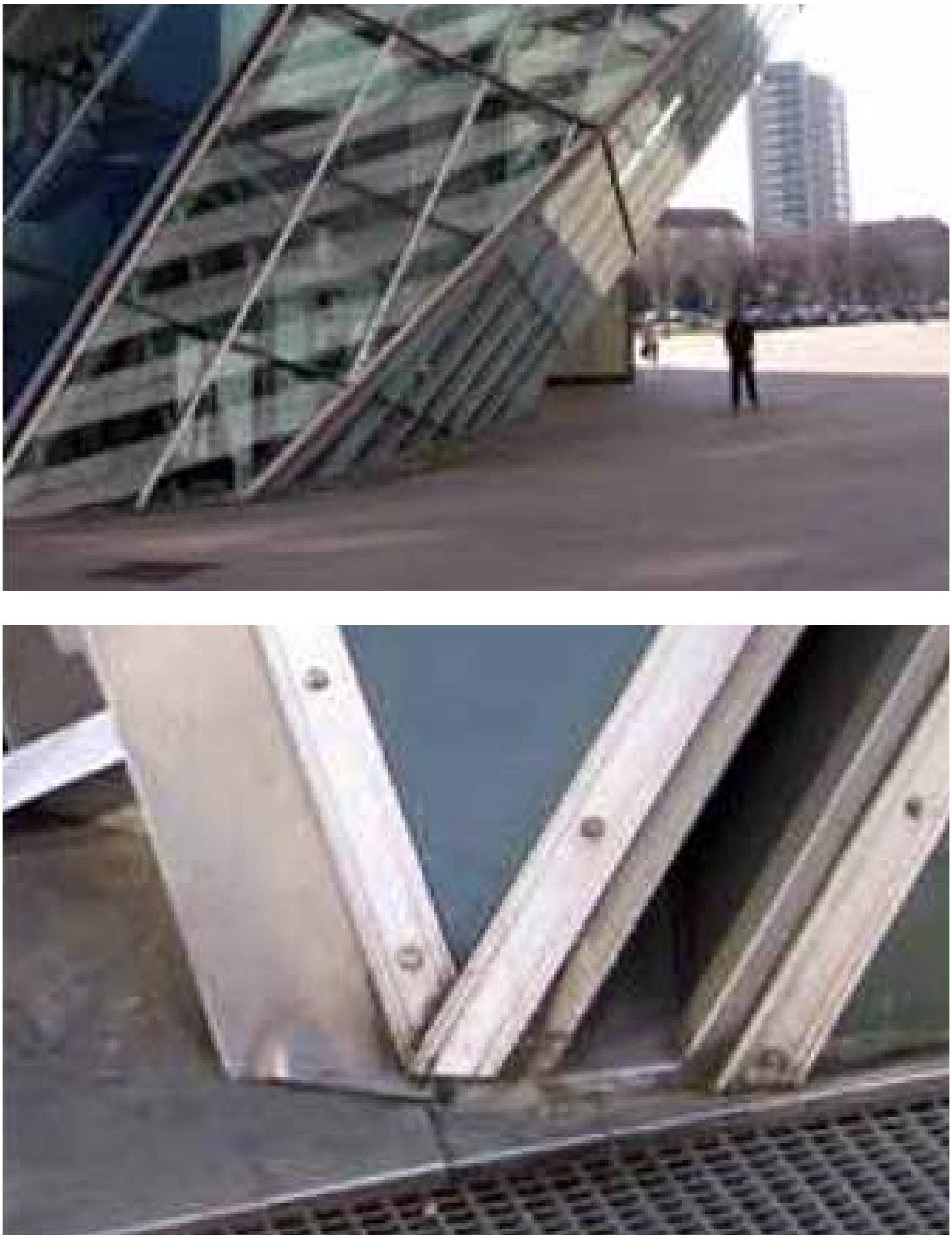


Figure 1.1.5: Non orthogonal façade construction, resulting in a joining detail that is inadequately solved with silicone.
Source: Strauß, 2017

1.2
Research Objectives

As AM Technologies are advancing both in terms of their capabilities and their accessibility, many industries are beginning to wonder what the potential of AM is in their industry, and how it might stand to revolutionize the nature of their product, uninhibited by limitations of manufacturing methods. The steel facade industry is one such industry, who recognizes the value of AM in response to sustainability objectives, the desire for high-transparency enclosures, and increasing demand for free-form facades.

This research proposes the research by design of an additively manufactured parametric node that is capable of overcoming the performance and structural challenges of free-form glass facades. This research also seeks to explore how the application of additive manufacturing has the potential to improve the performance of the existing traditionally manufactured solution. A SWOT Analysis (Figure 1.2.1) undertaken by Huzefa Ali in Rationalization of Freeform Glass Façades From Concept to Construction (2013) outlines the strengths, weaknesses, opportunities, and threats of the free-form glass façade Industry. This research seeks to find a solution that where possible, highlights and improves upon the strengths of the industry, and improves on its weaknesses by taking advantage of additive manufacturing, which is one its noted opportunities.

The purpose of this research is to explore the potential of additive manufacturing in steel curtain wall manufacturing in order to ultimately develop a prototype of a steel node for hybrid systems consisting of standard stick-framed steel facade elements and custom 3d printed joints. This research requires developing a thorough understanding of steel curtain wall systems in order to develop a system that is truly beneficial to the industry. Also, a thorough understanding of rapid manufacturing technology's necessary, focusing on both its present applicability and the direction in which this innovative technology is headed.

In a 2015 article published by Deloitte University Press on integrating additive manufacturing into industries and businesses, the authors illustrate a quadrant with four paths to AM integration and their potential value (Figure 1.2.2). Each path is defined by the presence or absence of change to the product, and change to the supply chain. This research will limit itself to Path III: Product evolution, in which there is a change in product and no change to the overall supply chain. This path is chosen specifically because it provides a viable solution in the near-future specific to the steel curtain wall industry to overcome the challenges outlined in previous sections.

A secondary objective of this research is to gain an understanding and experience of the digital process of taking a design from conception through optimization and additive manufacturing. While there are many digital tools and platforms available for this type of application, the development of an effective digital workflow is necessary in order to make this process as seamless as possible to maximize the value of the end product.

1.3
Relevance

The specific nature of this research is driven by the intersection of several current trends in the building envelope industry: the increasing structural requirements for building enclosures due to sustainability objectives and a drive for maximum transparency; the increase of parametric design in architecture and subsequent increase in popularity of free-form facades; and the quickly advancing capabilities and accessibility of 3d printing technology. The steel curtain wall industry, which directly faces the challenges brought on by some of these trends, is an excellent opportunity to explore how additive manufacturing has the potential to improve existing products and systems.

Strengths	Weaknesses	Opportunities	Threats
Risk taking	Risk management	Lack of Client /Architect technical knowledge for complex structures	Imbalance of Client/Supplier knowledge
Good margins	Role confusion	Increasing performance demands	Regulations – sustainability
Technical knowledge coming from the specialized market	Poor site skills and lack of training	CAD/CAM and BIM manufacturing	More economical buildings but poor quality
Flexible supply chains	Fragmented specialized industry	Advances Innovative technology and research investments.	Changing Architectural trends
Proven technologies by testing of Bespoke components	Lack of trust and coordination	Niche markets and less competition	Global competition
	Lack of understanding the need of training and effort to put in design.	Value engineering	Onerous contracts Inertia
	Lack of documentation		Incompleteness of design

Figure 1.2.1: SWOT Analysis for
Source: Ali, 2013

Figure 1.2.2: Framework for understanding AM paths and potential value
Source: Michalik, Joyce, Barney & McCune, 2014

1.4
Research Questions

Main Research Question:

► How can additive manufacturing technology be used to improve the manufacturing and design of steel facades?

Sub-Questions:

► What are the strengths and limitations of current standard steel curtain wall systems?

► What are the strengths and limitations of the various common metal additive manufacturing technologies?

► What are currently the most appropriate methods of metal additive manufacturing available for application in free-form curtain walls?

► What are the industry trends and emerging technology that have potential for application to AM steel curtain wall systems in the near future?

► How can additive manufacturing technology potentially improve steel curtain wall fabrication?

► How can additive manufacturing technology potentially improve steel curtain wall assembly?

► How can additive manufacturing technology potentially improve steel curtain wall performance?

► How can additive manufacturing change the design of traditional steel curtain wall elements?

1.5
Research & Methodology

There are three major areas of research in this study: steel curtain walls, steel additive manufacturing technology, and design for AM.

The first part of this research is based primarily on industry insight from professionals at Jansen Group in Switzerland where I spent several weeks learning about the design and fabrication of the existing systems, their strengths and limitations, as well as the future design ambitions of the team at Jansen. This part of the research is also partially based on literature to gain an understanding the history of curtain wall design, to gain further insight into the technical aspects of steel curtain wall design, and to gain an understanding of the material properties and characteristics of steel.

The AM portion of this research will focus on building knowledge through formal and informal literature around the available technology for steel additive manufacturing, as well as precedents of AM application in the construction industry and in other industries, and an inverstigation of current and expected developments in the technology.

During the research by design phase, a potential product for application in a steel curtain wall system will be selected and designed to embody the improvements previously identified. The product will be designed to improve the design and performance of the standard steel curtain wall using number of digital platforms. It will then further be optimized to add value to the design taking advantage of the digital design process in place.

1.6
Literature Review

Overall Framework

Several key texts are used to help establish a framework for this research. Both Integral Facade Construction by Tillmann Klein and AM Envelope by Holger Strauß look at additive manufacturing as a potential improvement in curtain wall manufacturing and performance, and discuss many of the specific considerations in the application of this newly accessible technology. These texts and others will help establish guiding factors for the design portion of the research, namely the potential applicability of 3d printed steel in the curtain wall industry, the metrics by which the 3d printed product should be measured, and the various design parameters that should be considered in the prototype.

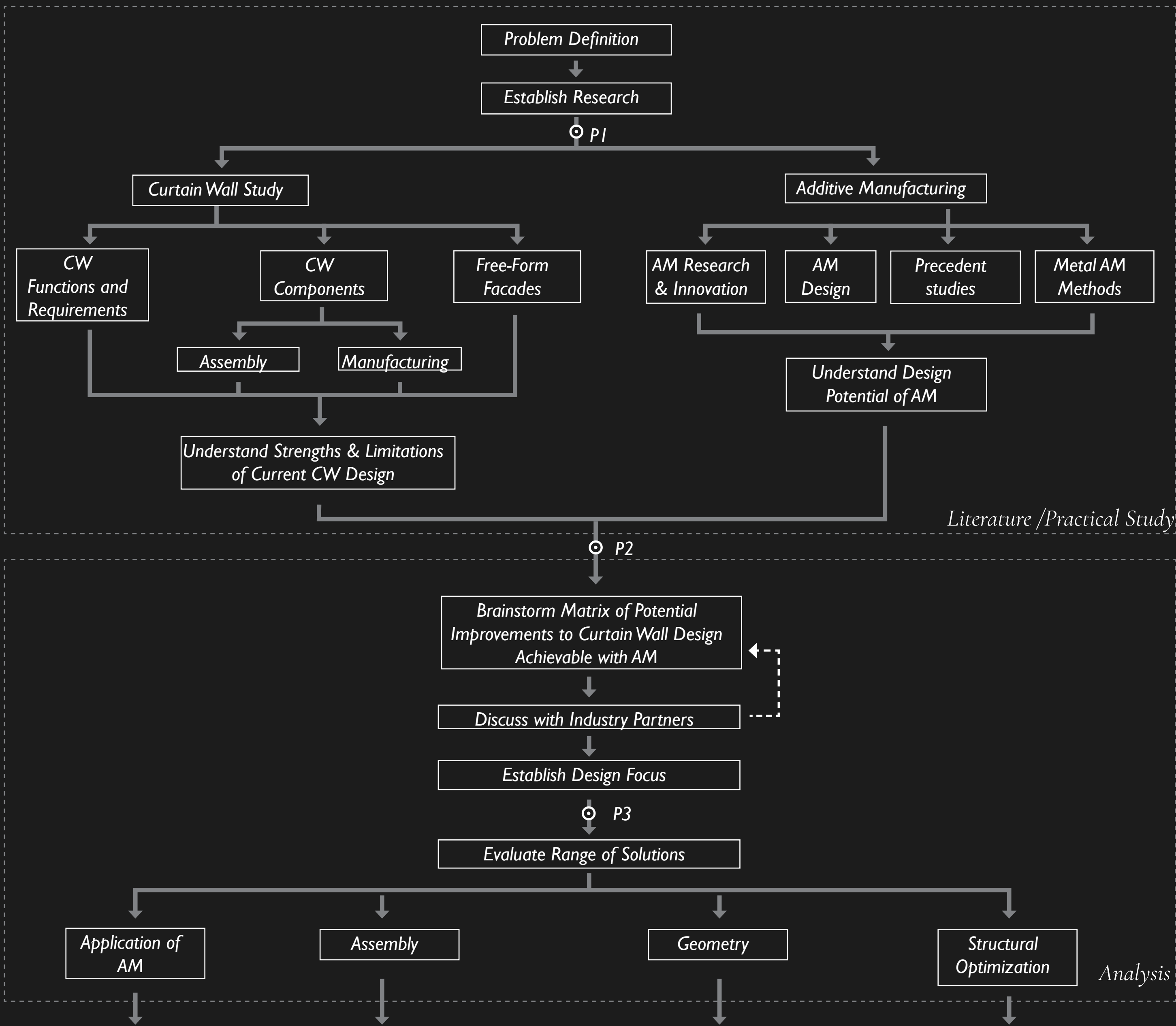
Steel Curtain Walls

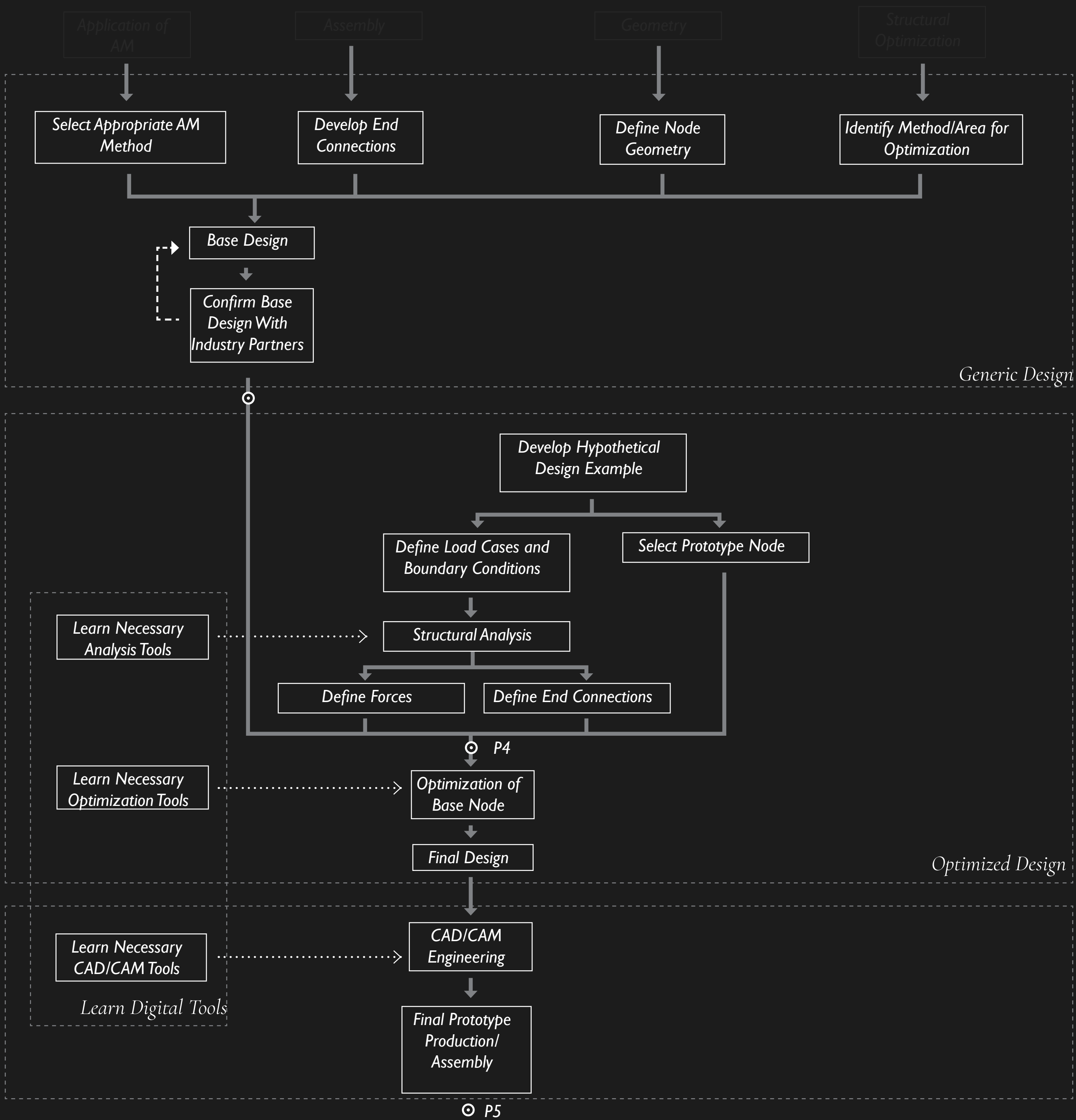
Most of the research in this report pertaining to technical aspects of curtain walls stems from the practical knowledge gained from industry professionals, and a thorough study of available design documents by common facade product distributors. Integral facade contructionn is also referenced for this purpose, as it provides quality insight into the specific functions of curtain wall components. Other literature pertaining to steel curtain wall structures include technical documents such as the The Curtain Wall installation Handbook published by the Centre for Window and Cladding Technology. This document along with several others are used to supplement the information gathered during learning visits at Jansen to help identify the various metrics by which the curtain wall is evaluated, and to identify the strengths and weaknesses of the modern assembly. CES is also used as references to help identify and gain an understanding of the manufacturing of the various curtain wall elements. Finally, reticulated structures on free-form surfaces by Soeren Stephan, Jaime Sanchez, and Klaus Knebel, as well as Rationalisation of freeform glass façades from concept to construction by Huzefa Ali are used as a sources for understanding the geometrical challenges and rationalization for freeform curtain walls.

Additive Manufacturing

Additive manufacturing is a rather modern and rapidly advancing field that is of great interest in the academic world and in industry, and is increasingly frequently documented. This research utilized, in addition to the previously mentioned pertinent texts, two more texts specific to the additive manufacturing of metals: Additive Manufacturing of Metals: The Technology, Materials, Design and Production; and Additive Manufacturing of Metals; From Fundamental Technology to Rocket Nozzles, Medical Implants, and Custom Jewelry. These texts were selected because they were published by Springer, a reputable science and technology publisher, and also because they were published very recently, namely in the year during which this research was commenced, ensuring that in a rapidly evolving industry, that the information was as recent and relevant as possible. A collection of other texts were also reference to obtain information about very specific subjects within metal additive manufacturing. Since a relevant part of this research is understanding the direction in which the industry is headed, various blogs, vlogs and webinars were also referenced as a way of gaining insights on industry opinions and trends.

1.7
Research Scheme




Application of AM
Assembly
Geometry
Structural Optimization
Select Appropriate AM Method
Develop End Connections
Define Node Geometry
Identify Method/Area for Optimization
Base Design
Confirm Base Design With Industry Partners
Generic Design
Develop Hypothetical Design Example
Define Load Cases and Boundary Conditions
Select Prototype Node
Learn Necessary Analysis Tools
Structural Analysis
Define Forces
Define End Connections
P4
Learn Necessary Optimization Tools
Optimization of Base Node
Final Design
Optimized Design
Learn Necessary CAD/CAM Tools
CAD/CAM Engineering
Final Prototype Production/ Assembly
Learn Digital Tools
P5

02
Curtain Walls

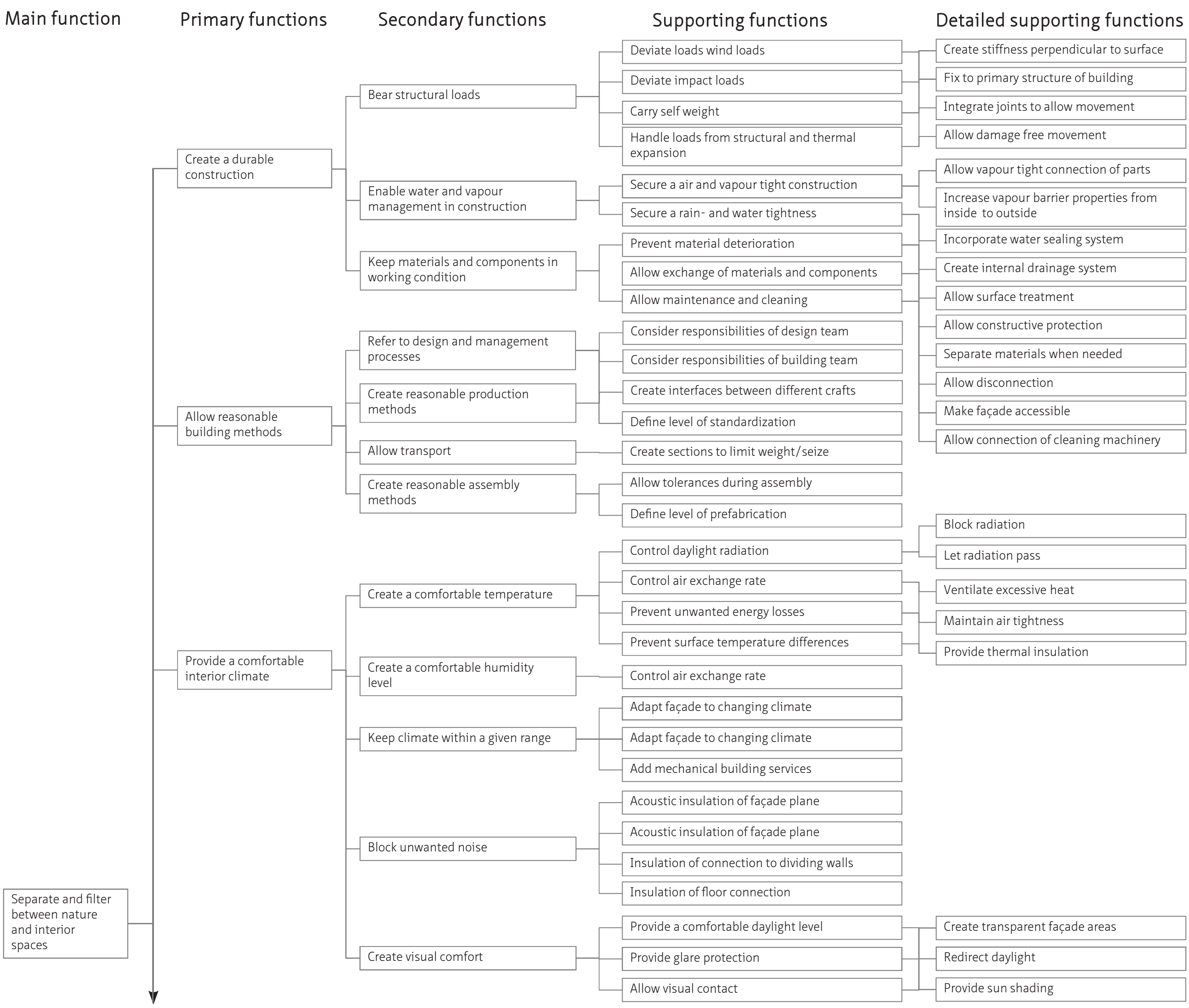
The modern definition of a curtain wall, as generally understood in the industry, is a subcategory of building envelope whose structure is independent of the buildings main load bearing structure (Knaack et al.). The origin of the curtain wall can be traced back to the introduction of frame construction in the mid 1800s, which decoupled the load bearing function of the enclosure from that of the main structure and set the stage for the development of lightweight enclosures (Yeomans, 1998). Since then, the curtain wall has evolved to have a range functionalities that range from integrating elements for solar protection, to energy generation, to hosting commercial advertisements.

The materiality of many of the elements in the curtain wall assembly can vary. A wide range of panel material are available depending on the desired aesthetic and other factors such as level of opacity of the building enclosure. Such materials can include glass, aluminium, stainless steel, and stone. One of the most popular advantages of the curtain wall is that its non-load bearing property allows for large transparent expanses (Klein, 2013). Structural systems are typically aluminium or steel, depending primarily on factors such as cost, required structural performance, and desire level of prefabrication. Cable-net structures are also increasingly popular due to their high level of transparency and inherent lightness.

Specific minimum standards building requirements for curtain walls are published in the European Standard EN 13830. This document is prepared under mandate from the European Commission and the European Free Trade Association to act as national standard for members of the European Union. Performance requirements are subdivided into five main categories and each include variations of basic characteristics, calculations and physical testing to establish adequate performance, energy use, safety and serviceability of building envelopes.

2.1
Curtain Wall Functions

The curtain wall system has a series of requirements for which it is responsible. These requirements have become increasingly more stringent over time and influenced the development of commercially available curtain wall systems. The most basic requirements for a curtain wall, as illustrated in the "façade function tree" developed by Joep Hoevels (Klein, 2003), consist of primary functions such



as durability, coherency with available building methods, the provision of a comfortable interior environment, being considerate of environmental consequences, support of the building function, and the spatial formation of the building exterior. Each of these primary objectives can be further subdivided into increasingly specific secondary functions, supporting functions, and detailed supporting functions. As basic requirements are met, with innovation in material science and technology, we are able to become increasingly ambitious as an industry in our fulfillment of these requirements.

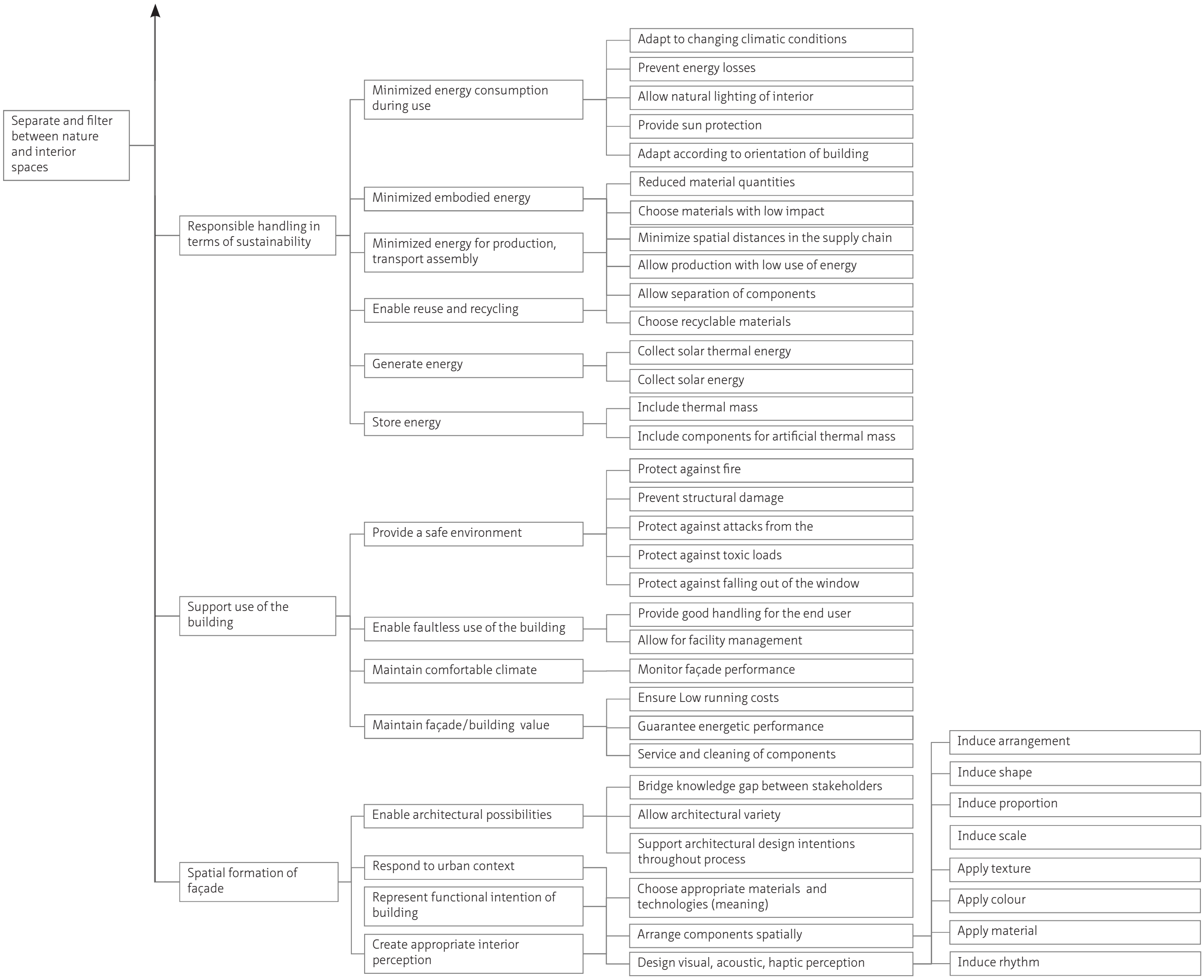


Figure 2.1.1: Façade function tree
Source: Klein, 2013

2.2
Curtain Wall Classifications

There are six primary classifications of curtain wall construction based on manufacturing, installation and mechanical features of the curtain wall system (Afghani Khoraskani, 2015): Stick-Built; Unitized; Panelized; Spandrel panel ribbon glazing; Structural sealant glazing; and Point-fixed Structural glazing. The following section is a description of these systems based on Chapter 2: Architectural Glazing from Advanced Connection Systems for Architectural Glazing.

Stick-Built

The Stick-Built system (Figure 2.2.1) is characterizes by its use of individual transom and mullion elements, typically extruded aluminium or cold rolled steel,that are cut to length and assembled on site. The range of applications for stick-built systems is wide. Advantages of the system are that it is simple and suitable for irregular shapes. Disadvantages include that it has a low level of prefabrication compared to other curtain wall system, and requires on-site installation which can result in negative effects to performance and quality control, which is largely dependent on the quality of the installation team.

Unitized

Unitized systems (Figure 2.2.2) are characterized by the use of modules of pre-assembled glazing panels manufactured in factory conditions. Their frame which typically spans a single story and is typically of extruded aluminium, connects back to the main structure of the building at floor slabs. Advantages of the system are that it is very convenient and cost-effective in terms of assembly, which in some application can also be a cost-saving measure. Unitized systems have comparatively superior performance and quality control than many other classifications. Disadvantages are that the product itself is more complex and more expensive. Since these systems are often manufacturer installed, they often come with good performance guarantees or warranties.

Panelized

Panelized systems (Figure 2.2.3) are similar to unitized systems, the main difference being that panelized systems are much larger. These systems are mostly used when they can be attached directly to the main structure. Panelized systems can typically support heavier cladding materials, and have structural advantages as they reduce deflection of the slab at midspan.

Spandrel Panel ribbon

Spandrel panel ribbon systems (Figure 2.2.4) consists of long prefabricated glazed panels between top and bottom spandrel panel fixed to the floor slab. Advantages are similar to panelized systems. This system has a very distinct horizontal aesthetic.

Structural sealant Glazing

Structurally sealed glazing (Figure 2.2.5) is characterized by the chemical fastening of the glazing unit to the assembly using silicone, rather than mechanical fastening such as pressure plates and gaskets. Structural Sealant Glazing can be used in combination with other classifications of curtain walls. Aesthetically, they have a smooth external surface which is desired by many architects. This classification is also suitable for complex geometry.

Point-Fixed Structural Glazing

Point-Fixed Structural Glazing (Figure 2.2.6) is characterized by the minimization of support elements which are reduced to metallic fixings at corners and sometimes edges of panel elements. The system can be combined with various forms of back-up structure including space structures, mullion and transom structures, cable net structures, etc. These systems allow maximum transparency. They require structural sealant and the use of toughened/laminated glass.

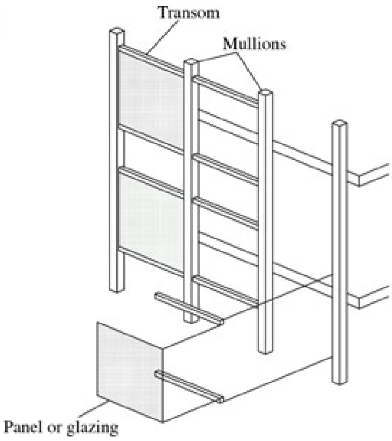


Figure 2.2.1: Stick-Built System
Source: Afghani Khoraskani, 2015

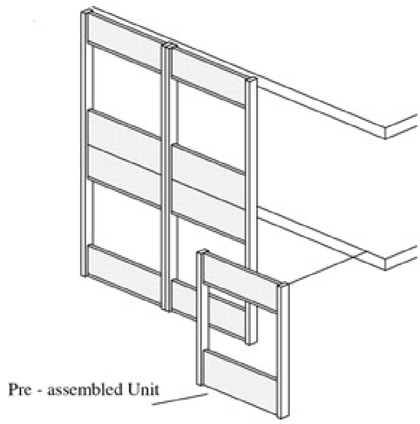


Figure 2.2.2: Unitized System
Source: Afghani Khoraskani, 2015

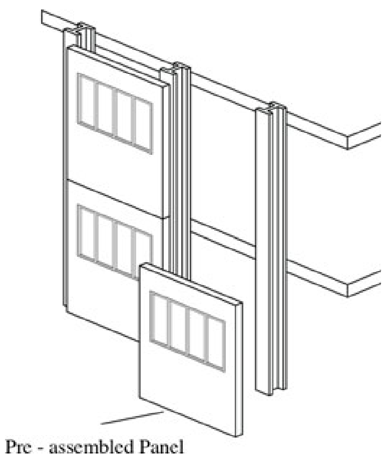


Figure 2.2.3: Panelized System
Source: Afghani Khoraskani, 2015

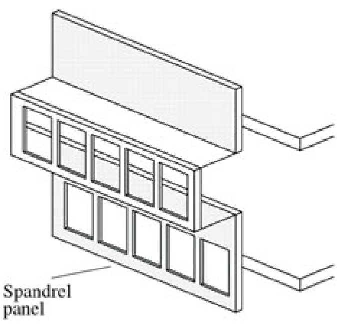


Figure 2.2.4: Spandrel Panel Ribbon System
Source: Afghani Khoraskani, 2015

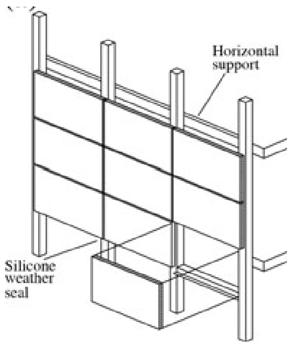


Figure 2.2.5: Structural Sealant Glazing
Source: Afghani Khoraskani, 2015

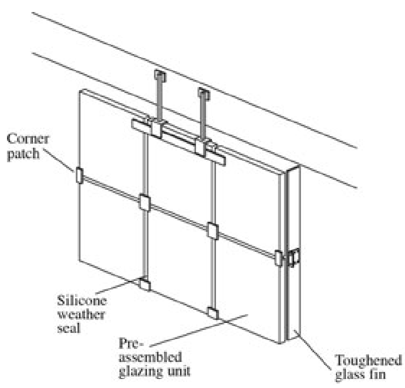


Figure 2.2.6: Point Fixed Sutrctural Glazing
Source: Afghani Khoraskani, 2015

This project will focus on the use of a stick-built system, due to its outlined advantages of being appropriate selection for free-form enclosures. The disadvantages of the system, namely that it requires substantial on-site assembly, and that its quality and performance is subject to the quality of manual labor, are potential opportunities for the application of additive manufacturing to improve the system.

Figure 2.2.7 connects detailed supporting functions of the enclosure to their respective elements in a stick-built system, outlining the role of each component in the curtain wall system in the overall performance of the enclosure system. The decoupling of elements indicates that a change can be made to one components without having to require change to the other (Klein, 2013) for the overall system to work correctly. This creates the basis for the kit of parts created by facade manufacturing companies to maximize aesthetic possibilities with a single system design.

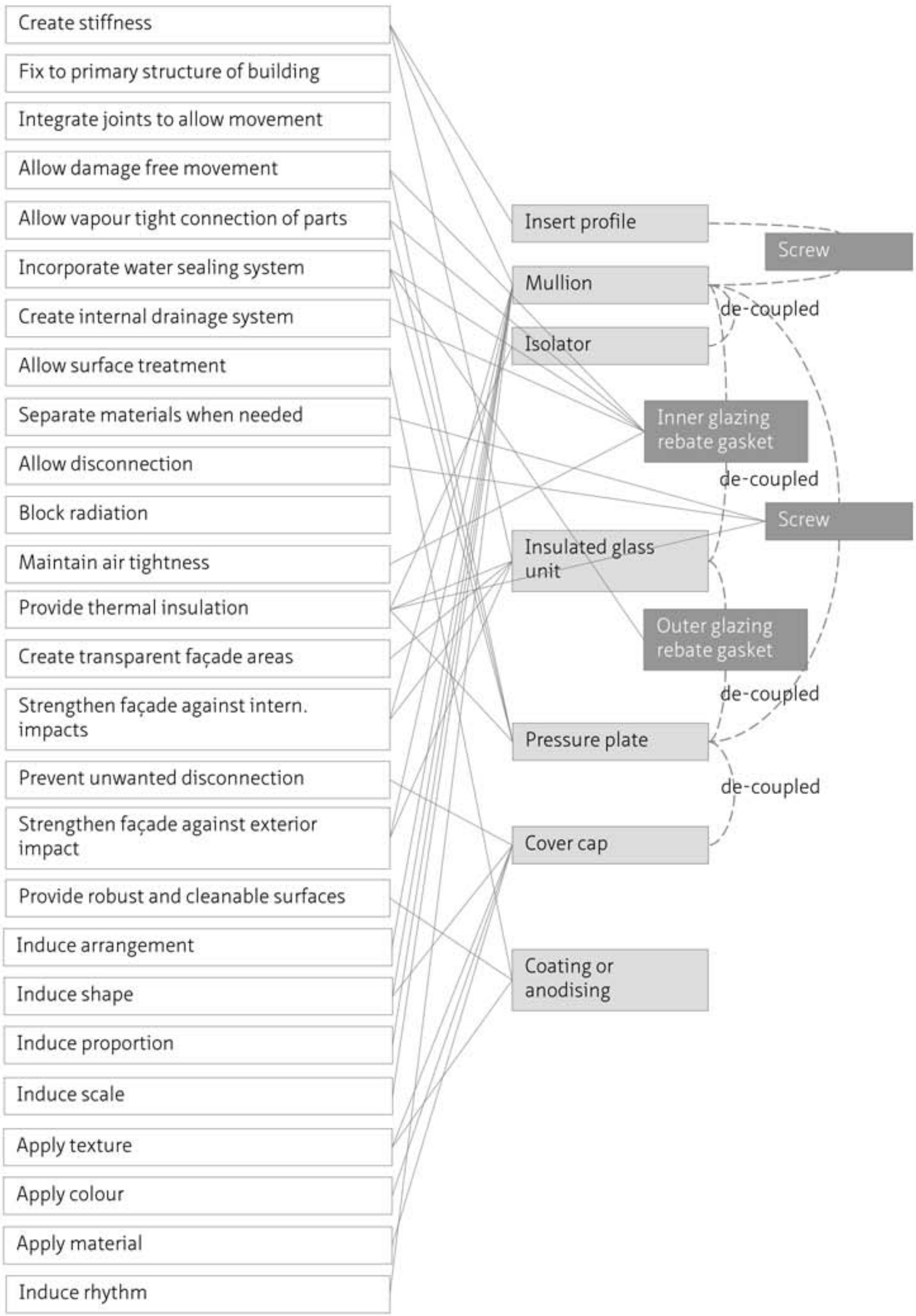


Figure 2.2.7: Function structure of contemporary curtain wall
Source: Klein, 2013

2.3
Steel vs. Aluminium Curtain Walls

The mains structural components for stick framed curtain wall systems are typically fabricated from three primary materials: aluminium, steel, and stainless steel. These materials are used to for the components that take on the structural bearing functions outlined in the facade function tree. These members need to take on the self weight of the curtain wall, wind loads, impact loads, and loads from structural and thermal expansion. As previously mentioned, the selection of one system of another can vary depending amongst other factors on structural capacity, cost, and desired level of prefabrication. While steel and stainless steel systems are quite similar in terms of their components and assembly, aluminium systems have quite a different make-up. These differences are due largely to the different structural behavior and manufacturing capabilities of the materials.

A comparison of the properties of the two materials illustrates some of the reasons one might select one system over another. Table 2.3.1, which contains data from CES for Low Carbon Steel category S235 and Aluminium 6000 series, which are commonly used in curtain wall construction, highlights the strengths and weaknesses of steel and aluminium as raw materials, which helps to inform system selection, and begins to provide insight into the potential of what additive manufacturing could help achieve in 3D printing a curtain wall system. The following sections are a summary of considerations for each a steel and aluminium curtain wall systems. Figures 2.3.1 and 2.3.1 illustrate respectively a steel and a unitized aluminium curtain wall section with similar Ix values.

	Steel (Low-Carbon)	**Aluminium** (6000 series)	Unit
General Properties			
Density	7,8e3 - 7,9e3	2,7e3 - 2,73e3	kg/m^3
Price	0,573 - 0,689	1,73 - 1,82	EUR/kg
Mechanical Properties			
Young's modulus	200 - 215	68 - 71,5	GPa
Shear modulus	79 - 84	26 - 27,3	GPa
Yield strength	250 - 395	103 - 124	MPa
Tensile strength	345 - 580	172 - 241	MPa
Thermal/Combustion Properties			
Max service temperature	340 - 357	77 - 180	°C
Processability (1 to 5 rating)			
Castability	3	4-5	
Formability	4-5	3-4	
Machinability	3-4	4-5	
Weldability	5	3-4	
Raw (uncoated) Material Corrosion Resistance			
Water (fresh)	Acceptable	Excellent	
Water (salt)	Limited Use	Acceptable	
Primary material production			
CO2 footprint, primary production	1,72 - 1,9	12,2 - 13,5	kg/kg
Water Usage	43,2 - 47,7	1,13e3-1,25e3	l/kg

Table 2.3.1: Comparison of Steel and Aluminium Properties
Data Source: CES 2017

Steel Curtain Wall Systems

+ Stiffness is approximately 3x that of aluminium. This allows many structural advantages, which include larger allowable glass spans, heavier loads, and smaller sections, which result in less visual obstruction and potentially quicker installation.

+ Better maximum service temperature is advantageous for applications with stringent fire safety requirements

+ Is a more weldable option. This enables simple moment connection of elements which reduces deflection.

+ Lower thermal expansion than aluminum

- Is generally a more costly option than aluminium

- Manufacturing restrictions can only accommodate relatively simple section profiles

- Is prone to corrosion if not properly coated/maintained

- Is a heavier option than aluminium, which can have repercussions on the primary structure loads.

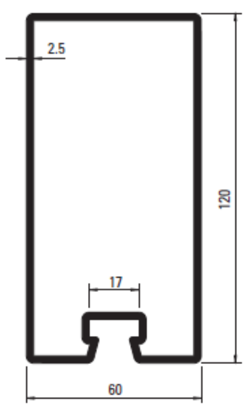


Figure 2.3.1: Steel Section - I_x:183 cm⁴
Source: Jasen AG, Sales Range

Aluminium Curtain Wall Systems

+ The lightness of aluminium system renders them ideal for application with significant building enclosure area such as high rise buildings.

+ The geometrical freedom achievable with aluminium systems enables more complex section profiles which in turn enable the application of additional features to the curtain wall profiles such as a unitized system, internal reinforcements, or raceways for efficient mechanical fastening.

+ Is generally a less costly option than steel

+ Has better corrosion resistance than steel

- Has an inferior structural performance to steel therefore requires larger sections profiles for same application, and can reasonably be applied to more limited spans.

- Is more prone to damage from service impact than steel

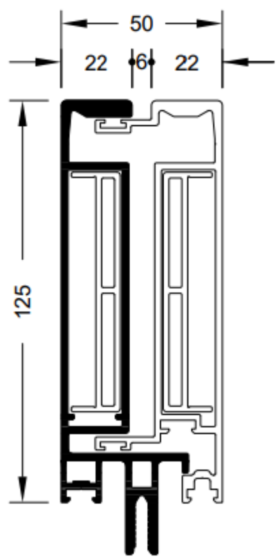


Figure 2.3.2: Unitized Aluminium Section - Ix: 181 cm^4
Source: Schuco

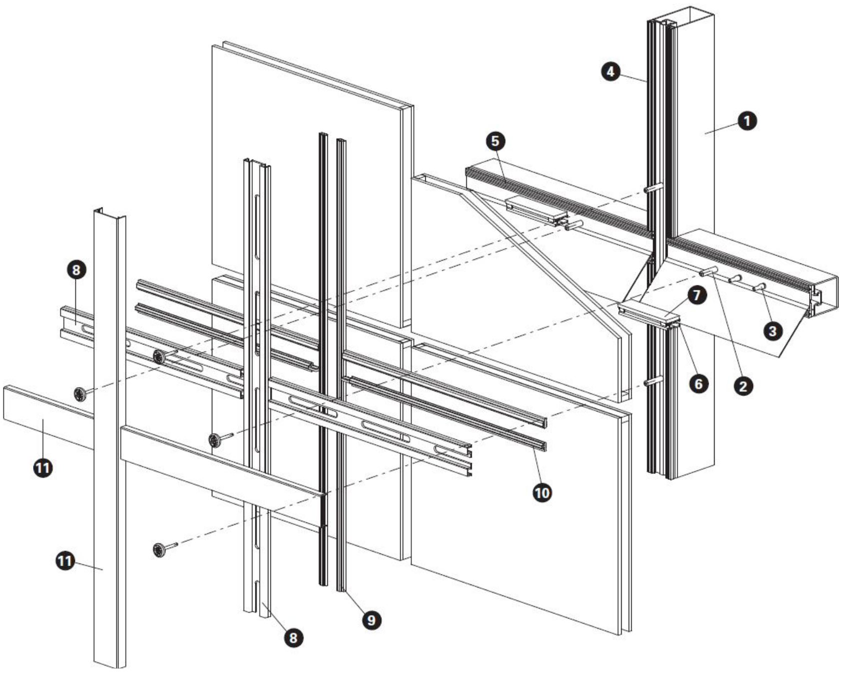
2.4
Jansen AG VISS Facade

The typical stick-built steel facade curtain wall system consists of an assembly of components that together, provide durable structural performance, as well as air, water, vapour, thermal and acoustic control for the building. The system must allow for structural and thermal movement, and be aesthetically pleasing. Each component in the steel curtain wall assembly contributes in one way or another to the tasks above.

Steel curtain wall systems vary from one manufacturer to another, as each typically produces its own proprietary system. These systems may vary in terms of their materiality, shape, cost, and performance, however each provides and assembly that at the very least abides by the performance standards defined by the various regional building authorities.

This research uses as a base system the VISS Facade System developed by Jansen AG, a steel systems developer, manufacturer, and distributor based in Switzerland. The system consists of a kit of parts that allows designers to select from a range of features and aesthetics. Features include added insulation, roof applications, structural glazing, fire resistance and burglar resistance. The kit of parts also includes a range of profiles for mullions and caps in order to provide a options that cater to different structural requirements and aesthetics preferences, as well as a range of different connection options with varying structural capacities and assembly methods. The system also comes with a range of compatible doors and windows that can easily be integrated into the facade. This project will use as a based model the VISS Linea, a baseline assembly for the system with a T-like shaped profile. The following section is an inventory of the various parts in the VISS Linea system and an overview of their functions.

System Components



1. Load-bearing structure
2. Insulating stud
3. Supporting bolt
4. Inside gasket vertical
5. Inside gasket horizontal
6. Rebate section
7. Glazing support
8. Clamping section
9. Outside gasket vertical
10. Outside gasket horizontal
11. Cover section

Figure 2.4.1: VISS Curtain Wall Components
Source: Jansen AG, VISS façade Processing and assembly

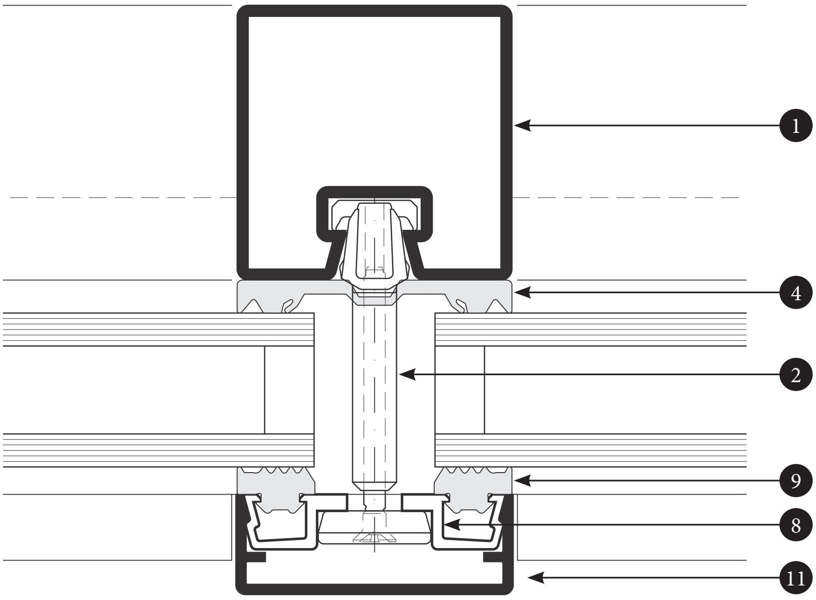


Figure 2.4.2: VISS System Vertical Section
Source: Jansen AG

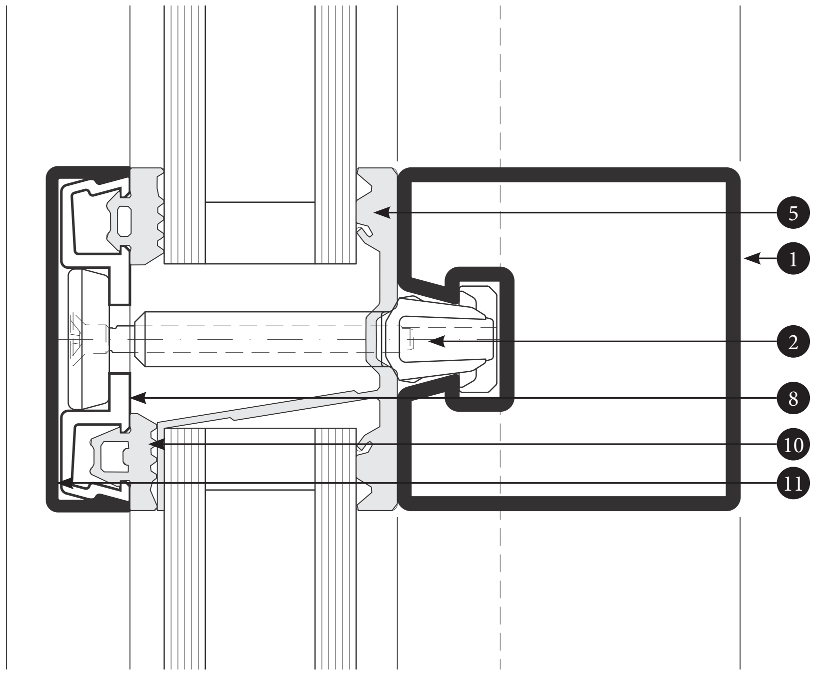


Figure 2.4.3: VISS System Horizontal Section
Source: Jansen AG

Load Bearing Structure

The load-bearing structure takes on the structural loads and provide stiffness for the curtain wall assembly. These members connect back to the primary structure of the building. The section profiles come in four main profiles: a rectangular profile, a tapering profile (commercial name Delta) a T-like profile (commercial name Linea) and a T-like profile with a solid steel flange. These are typically available in 50mm and 60mm widths, a range of depths between 18mm to 280mm depending on the profile, and in 2mm to 3mm thickness. Alternatively, the system can be configured with a few alternative parts to be attached to another steel profiles such as an I section without the recess for the supporting bolts and insulating studs, however this will not be considered in this application. This project will use as a base the hollow T-shaped profile as it provides the biggest challenge in term of geometric resolution.

The Load bearing structure can be connecting in 4 primary ways: welded connection; Push-on construction with universal connecting spigot; Push-on construction with clip-in connecting spigot; and Push-on construction with heavy-duty clip-in connecting spigot. Each Connection type has a different structural capacity, assembly sequence, geometrical freedom, cost, and required labor.

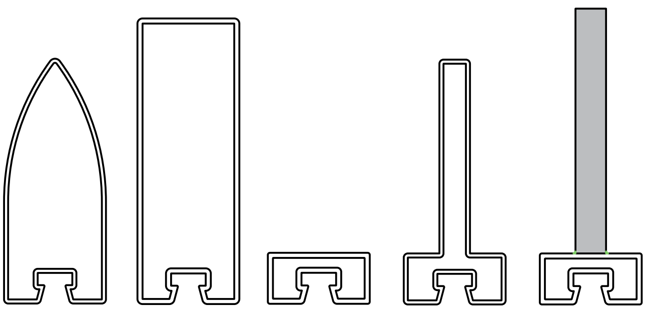


Figure 2.4.4: Range of Jansen AG Profiles
Source: Jansen AG

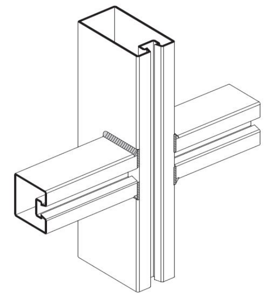


Figure 2.4.5: Unitized construction for welded transom
Source: Jansen AG, Viss Supporting Structure

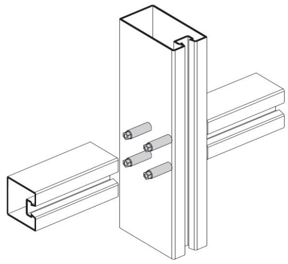


Figure 2.4.6: Push-on construction w/ universal connecting spigot
Source: Jansen AG, Viss Supporting Structure

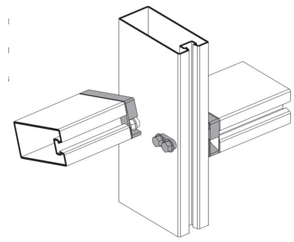


Figure 2.4.7: Push-on construction with heavy-duty clip-in connecting spigot
Source: Jansen AG, Viss Supporting Structure

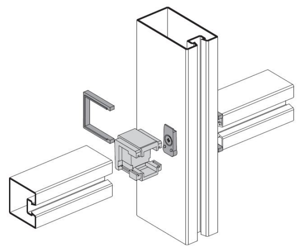


Figure 2.4.8: Push-on construction w/ clip-in connecting spigot
Source: Jansen AG, Viss Supporting Structure

Insulating Stud

The synthetic insulating studs secure the inner gaskets and more importantly retain the clamping sections while providing a consistent thermal break. The insulating studs consist of two parts: a female part synthetic sleeve that is locally inserted into the groove of the main steel profile, rotated into position and locked in place with a locking component that is pushed into the groove, and a male part screw with a large flat disk head to keep the clamping section securely fastened.

Figure 2.4.9: Insulating Stud
Source: Jansen AG, VISS façade Processing and assembly

Supporting Bolt

The supporting bolts are locally inserted into the groove of the main steel profile in order to provide a male support for the glazing support, transferring gravity loads to the main structural section. The supporting bolt is placed in the groove and rotated into place.

Figure 2.4.10: Supporting Bolt
Source: Jansen AG, VISS façade Processing and assembly

Interior Gasket Vertical

The inner vertical gasket provides a thermal break and a second line of air/water/vapour control for the enclosure. This gasket is secured to the structure with the use of the insulating studs. The gasket allows the glass to move due to building and thermal movement.

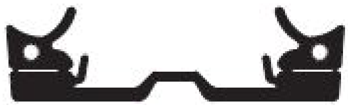


Figure 2.4.11: Inner Gasket Vertical
Source: Jansen AG, VISS façade Processing and assembly

Interior Gasket Horizontal

The inner horizontal gasket provides a thermal break and a second line of air/water/vapour control for the enclosure. This gasket is secured to the structure with the use of the insulating studs. The horizontal gaskets includes a lip that is folded over the front edge of the glazing below in order to guide any moisture towards the exterior face of the curtain wall. The gasket allows the glass to move due to building and thermal movement.

Figure 2.4.12: Inner Gasket Horizontal
Source: Jansen AG, VISS façade Processing and assembly

Glazing support

The glazing support is placed above the rebate section and beneath the glazing unit to protect the glazing unit from damage from the steel supports.

Figure 2.4.13: Glazing Support
Source: Jansen AG, VISS façade Processing and assembly

Rebate Section

The rebate section transfers the gravity load of the glazing units to the supporting bolts who transfer the load to the structure. The rebate section is an aluminium section that is snap fitted onto the supporting bolts

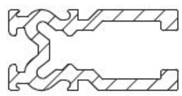


Figure 2.4.14: Glazing Support
Source: Jansen AG, VISS façade Processing and assembly

Clamping section

The clamping sections is an aluminium or stainless steel profile fitted with an exterior gasket that fastens the glazing unit to the structure by locking it between the interior gaskets and the clamping section, which is secured by the insulating stud.

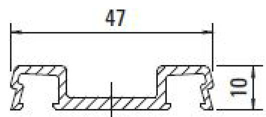


Figure 2.4.15: Clamping Section
Source: Jansen AG, VISS façade Processing and assembly

Exterior Gasket

The outside gasket vertical provides a first lines of air/water/vapour control for the enclosure. The gasket is fitted withing the clamping section to secure the glass. The lower portion of the horizontal gasket is fitted with small plastic stress-relieving inserts that allow for drainage. The gasket allows the glass to move due to building and thermal movement.

Figure 2.4.16: Outer Gaskets
Source: Jansen AG, VISS façade Processing and assembly

Cover Section

The cover section is a non-structural component that provides an aesthetic finish to the curtain wall assembly. The cover section snap fits onto the clamping section and requires joints to allow for movement. It is typically an aluminium of stainless steel profile for corrosion resistance.

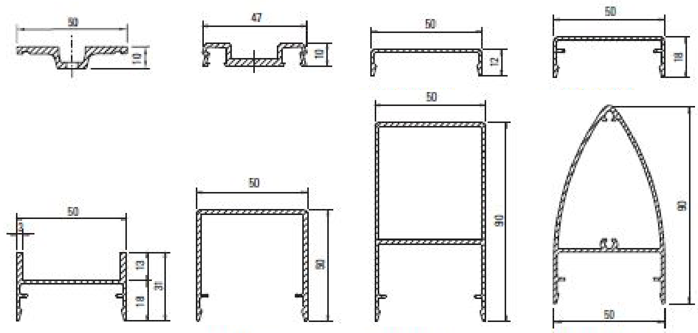


Figure 2.4.17: Selection of Aluminium Cover Sections
Source: Jansen AG, VISS façade Processing and assembly

System Flexibility

The kits of parts for the VISS facade system is able to accommodate glazing angles in the vertical plane of up to 30º (up to 15º on each side of the axis of the mullion).

The system can accommodate both concave and convex angles. The system gaskets (interior and exterior gaskets) accommodate the various angles, while the rest of the system remains the same.

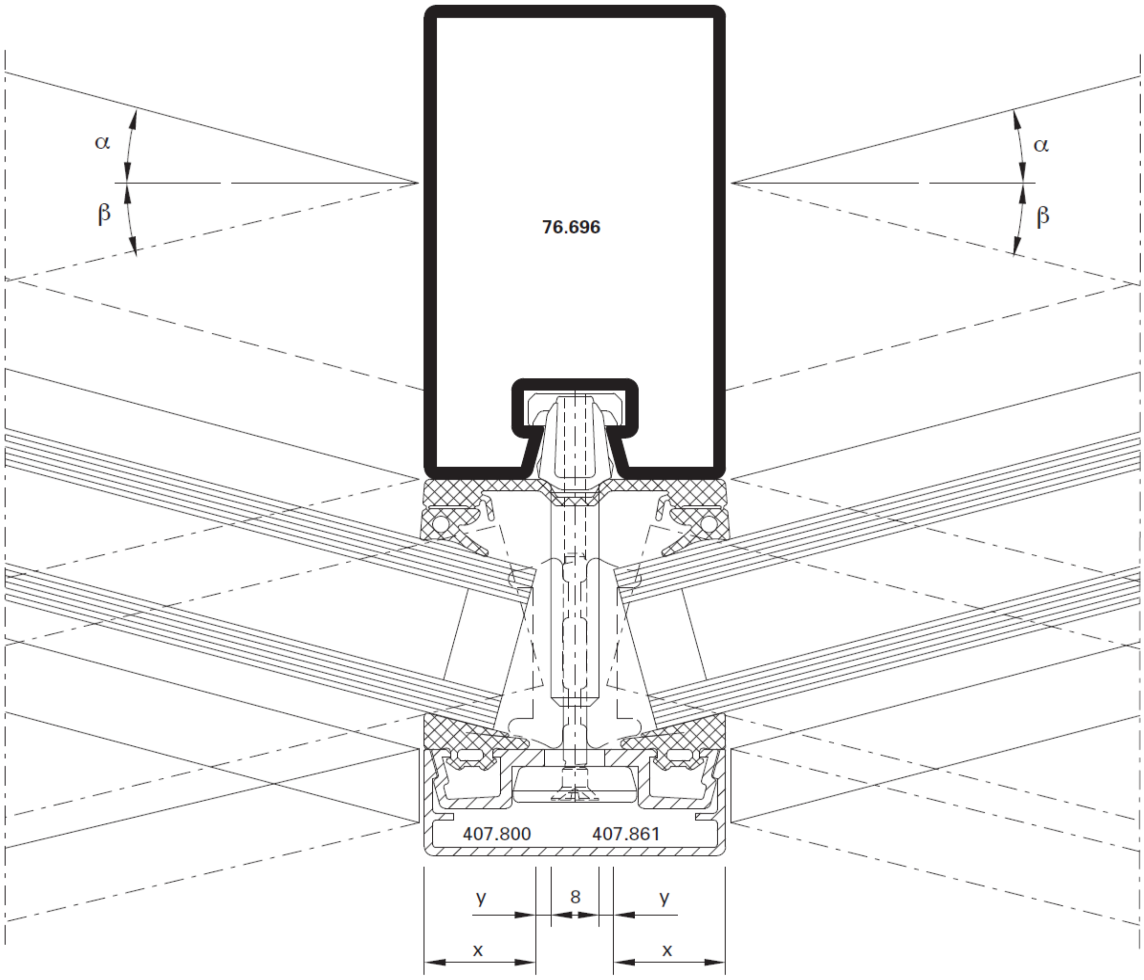


Figure 2.4.18: VISS System Flexibility
Source: Jansen AG, VISS Sales Range

Toolkit

The economical quality of the curtain wall system relies on a balance of economical production, and economical assembly. The manufacturing of the components is optimized in all of its aspects, from raw material acquisition, to fabrication, to storage and shipping, to be as quick and efficient as possible.

Economical Manufacturing

Many of the components in the assembly are extruded 2-dimensional profiles. This includes the main structural components, which are cold rolled and pressure welded, the cover cap and clamping sections which are either bent stainless steel or extruded aluminium, and the gaskets, which are extruded EPDM. Profiles are produced as continuous pieces. Metal sections are typically sectioned off at 6m lengths, and EPDM profiles are coiled. All pieces are cut to length during assembly.

Economical Fabrication

Because a large number of the components are produced as continuous profiles, part of the fabrication endeavor includes cutting profiles to length for assembly. The toolkit for the facade system is toolkit that is designed to maximize the efficiency of producing the system, providing quick power tools for quick tooling (drill and table saw) and minimizing the need for precise measurements (jigs and notching device). Figures 2.4.19 through 2.4.26 represent the necessary tools for the assembly of the push-on construction with universal connecting spigot curtain wall system. While these tools are very efficient for orthogonal system applications, they are limited in their ability to work for free-form systems. The vertical gasket notching device, for example, is designed to cut off the outer layer of gasket to allow for the horizontal gasket to come adjoin it. This gasket uses a specific blade attachment for a 90 degree cut. Another cutting insert would have to be fashioned for each individual angle, and the insert replaced for each individual cut. This, as you can imagine negatively affects the efficiency of the system.

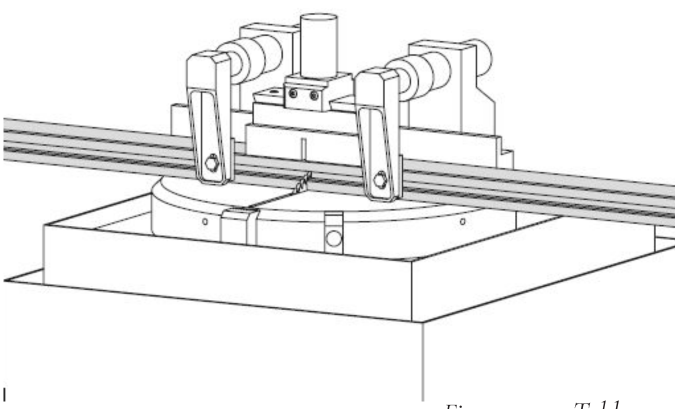


Figure 2.4.19: Table saw
Source: Jansen AG, VISS façade Processing and assembly

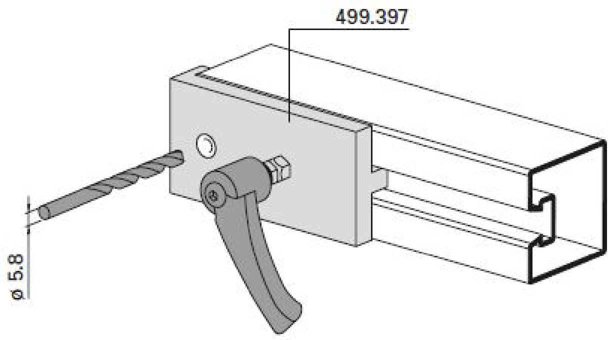


Figure 2.4.20: Drilling Jig for Transom
Source: Jansen AG, VISS façade Processing and assembly

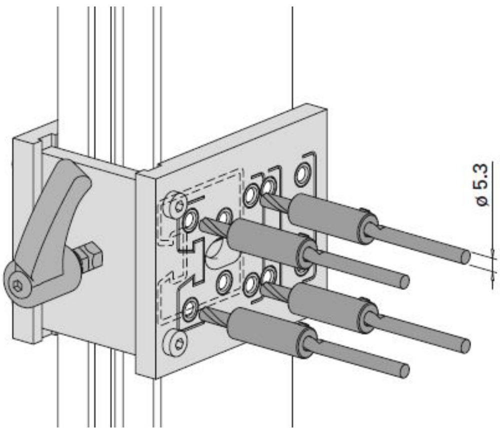


Figure 2.4.21: Drilling Jig for Mullion
Source: Jansen AG, VISS façade Processing and assembly

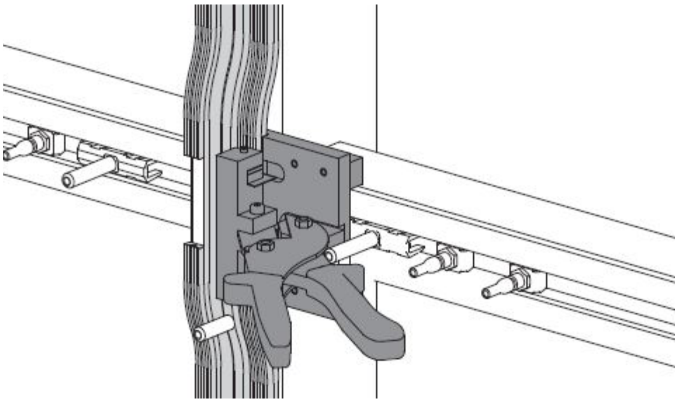


Figure 2.4.22: Gasket notching device w/ vertical attachment
Source: Jansen AG, VISS façade Processing and assembly

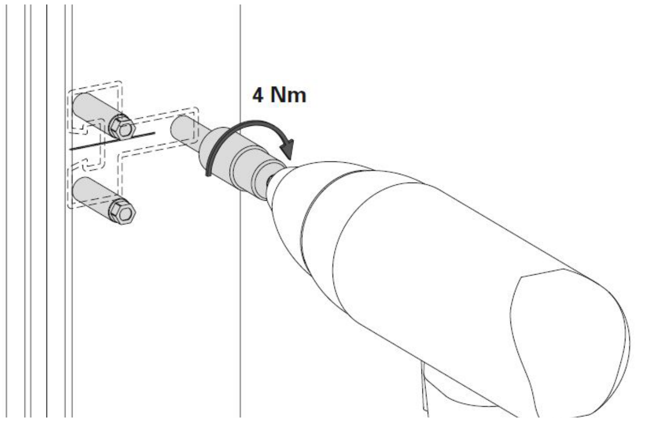


Figure 2.4.25: Drill w/attachment bit
Source: Jansen AG, VISS façade Processing and assembly

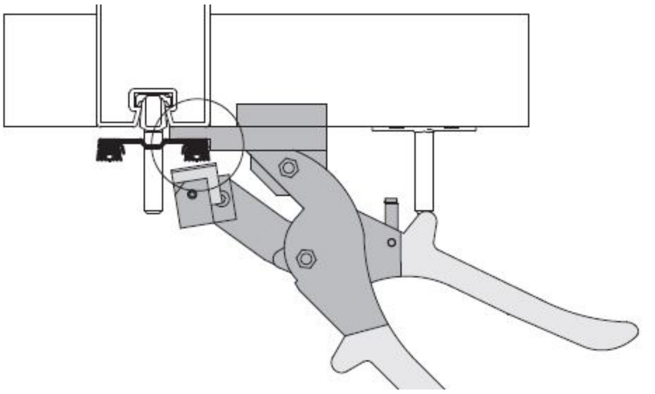


Figure 2.4.23: Gasket notching device with horizontal attachment
Source: Jansen AG, VISS façade Processing and assembly

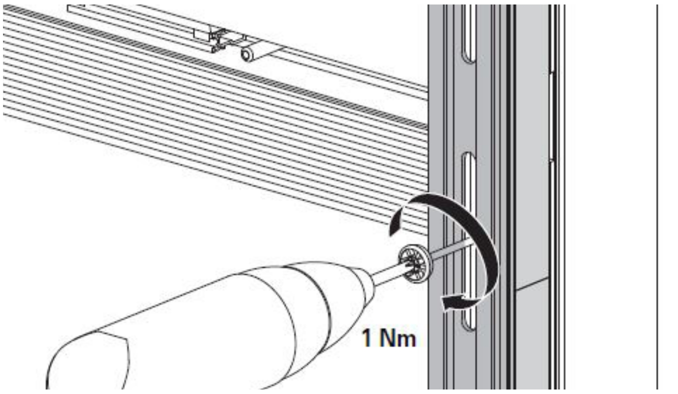


Figure 2.4.25: Drill
Source: Jansen AG, VISS façade Processing and assembly

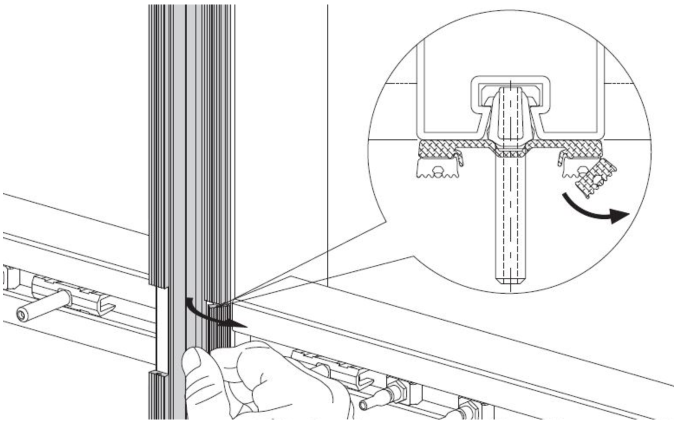


Figure 2.4.24: Diagram of removal of cut vertical gasket
Source: Jansen AG, VISS façade Processing and assembly

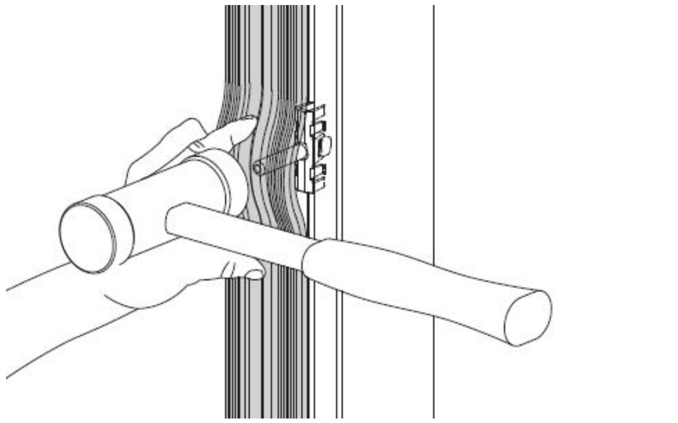


Figure 2.4.26: Nylon Mallet
Source: Jansen AG, VISS façade Processing and assembly

Connection Types

The VISS system come with 4 available ways of connecting the structural members of the curtain wall. Typically, as the system is configured for planar or simply-curved (meaning developpable surfaces such as cylinder (Stephan et al., 2004) applications, the vertical mullions run continuously and the horizontal transoms span between mullions. Each system varies in the mechanism is uses to create a structural connection, the assembly sequence that is enables, and the structural capacity and behavior of the connection. The available systems for the VISS System are the following:

1. Push on connection with connecting spigot
2. Push on connection with slip in connecting spigot
3. Push on connection with heavy-duty clip-in connecting spigot
4. Unitized construction for welded transom

In order to gain an understanding and illustrate the capacities of each system, they have been ranked in Table 2.4.1 by the author in terms of its structural performance, geometrical flexibility, ease of assembly, labor intensity, and cost from most favorable (1) to least favorable (4).In addition to this, Table 2.4.2 notes whether the system is capable of certain specific features. In analyzing this tabulated information as well as the assembly and product-data information for each system, a number of observations can be drawn about the existing connection types pertaining to their potential applicability to an AM version of the connection.

► Welded connection is the only option that allows for real geometrical flexibility, however it does not have any of the installation advantages of the other systems

► Welded connection is only system that has potential for prefabrication. Level of prefabrication is subject to factors such as transportation limitations.

► Welded connection is only system that is moment connected. All other systems are pin joints.

► Systems 2 3 and 4 enable installation between two fixed members, which is important for installation purposes of free-form facades.

► In systems 2 and 3, the connection pieces for the attachment are located on both the transom and the mullion. Option 1 is the only system in which the fastening piece is contained on the fixed piece. The advantage of this particular scenario is that transoms can simply be cut to length and installed without further prefabrication, and all the complexity is contained in a single element - in this case the vertical mullion.

► The overwhelming advantage of the welded joint its superior structural performance. The heavy duty clip-in connection is a close second. The load-bearing capacity of these systems is dependent on the profile, the connection and the type of glazing support. Tables 2.4.3 and 2.4.4 show a direct comparison of the bearing capacity of various connection systems for the same profile and the same supported connection. 50mm wide profiles 76.679 and 76.671 are shows in combination with welded support and 3 Structural Bolts (SB), respectively. In each case, the welded option has a superior bearing capacity.

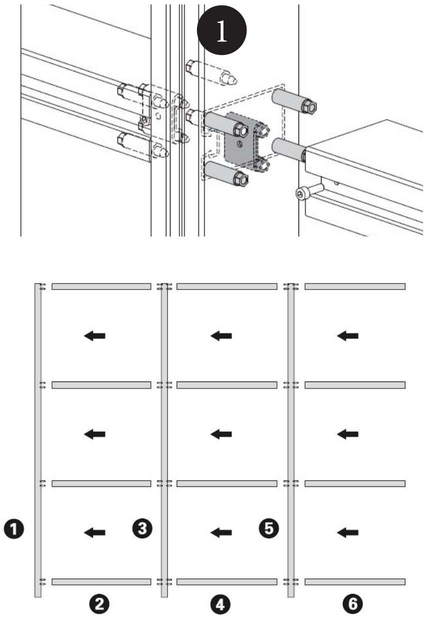


Figure 2.4.27: System 1: Push-on construction with Universal connecting spigot
Source: Jansen AG, VISS façade Processing and Assembly

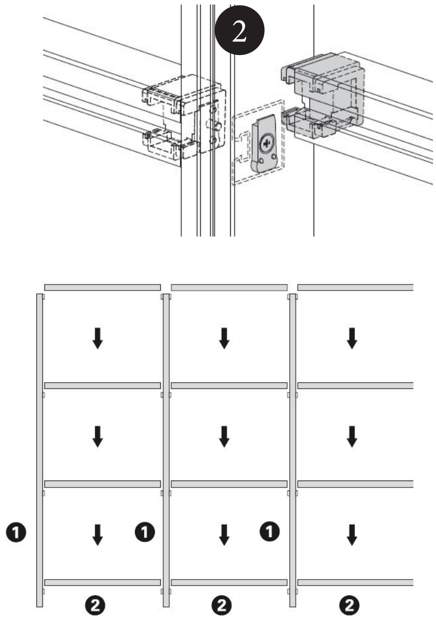


Figure 2.4.28: System 2: Push-on construction with clip in connecting spigot
Source: Jansen AG, VISS façade Processing and Assembly

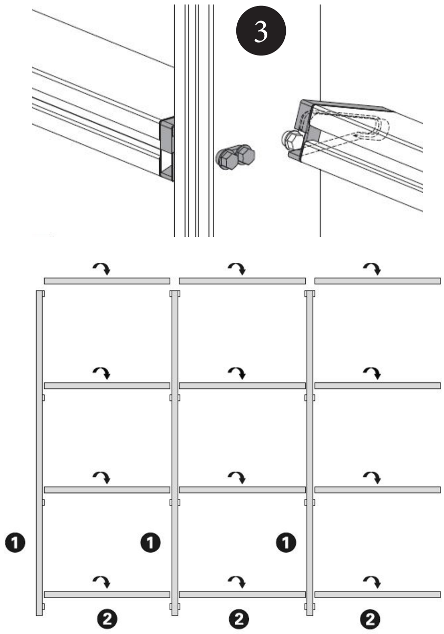


Figure 2.4.29: System 3: Push-on construction with heavy duty clip-in connecting spigot
Source: Jansen AG, VISS façade Processing and Assembly

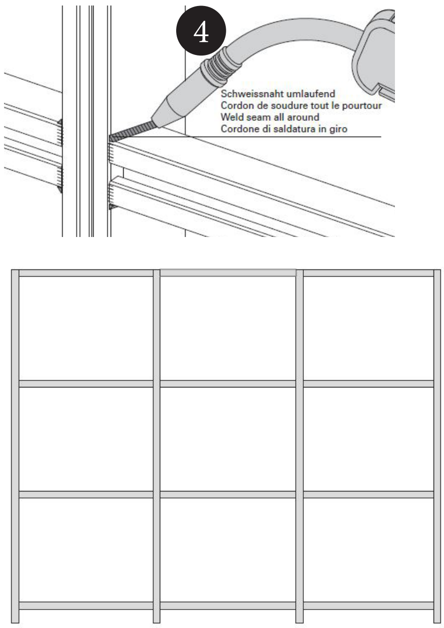


Figure 2.4.3: System 4: Unitized Construction for welded transom
Source: Jansen AG, VISS façade Processing and Assembly

	1. Universal connecting spigot	2. Clip-in connecting spigot	3. Heavy duty CI connecting spigot	4. Fully Welded
Load-Bearing Capacity	3	4	2	1
Geometrical Flexibility	4	4	4	1
Ease of Assembly (on-site)	1	2	3	4
Assembly Simplicity	1	2	3	4
Cost (Product, excluding labour)	2	4	3	1

Table 2.4.1: System Qualities: Best ranked (1) to worst ranked (4).
Source: Author

	1. Universal connecting spigot	2. Clip-in connecting spigot	3. Heavy duty CI connecting spigot	4. Fully Welded
Can accommodate free-form angles in one direction	N	N	N	Y
Can accommodate free-form angles in two directions	N	N	N	Y
Transom can be installed between two fixed members	N	Y	Y	Y
Can Be Prefabricated	N	N	N	Y

Table 2.4.2: System Capabilities: capable (Y) or not capable (N)
Source: Author

Connection System Type	Profile	Support	Capacity
1	76.697 x 50mm	Welded	5 kN
3	76.697 x 50mm	Welded	10 kN
4	76.697 x 50mm	Welded	12 kN

Table 2.4.3: Bearing Capacity Welded Connection
Data Source: Jansen AG, VISS Supporting Structure

Connection System Type	Profile	Support	Capacity
1	76.671 x 50mm	3 SB	2.5 kN
2	76.671 x 50mm	3 SB	1.5 kN
4	76.671 x 50mm	3 SB	3 kN

Table 2.4.4: Bearing Capacity w/ 3 Support Brackets
Data Source: Jansen AG, VISS Supporting Structure

2.5
Free-form Facades

The desire and determination in the industry to create free-form transparent facades has resulted in a number of truly impressive architectural projects in the past several decades. Innovative teams of architects, engineers and manufacturers have worked together to develop a number of different systems that have been able to achieve free-form building enclosures within the means of traditional manufacturing limitations. The DZ Bank in Berlin by Frank Gehry (Figure 2.5.1) constructed in 2001, the British Museum Court in London by Foster (Figure 2.5.2) constructed in 2000, and the New Fair in Milan by Massimiliano Fuksas (Figure 2.5.3) constructed in 2005 are all excellent examples of architecture that have embraced the possibilites of digital design and taken on the challenges of free-form transparent structures, developing innovative engineering solutions to achieve them.

As flat, simple forms, material reduction, and repetitive elements are some of the most effective ways of making architecture cost-effective (Henriksson and Hult, 2015), free-form architecture is in its essence a very non-cost-effective endeavor. One can imagine to achieve a fully free-form facade complete with thousands of unique pieces of double curved glass and structural elements would be an extremely expensive project. The industry has therefore come up with a number of strategies to help reduce the complexity of the geometry in such a way that it achieves complex forms but in a rather more cost effective way. These strategies revolve around rationalization and optimization. While both rationalization and optimization can be applied individually, they are most effective when integrated.

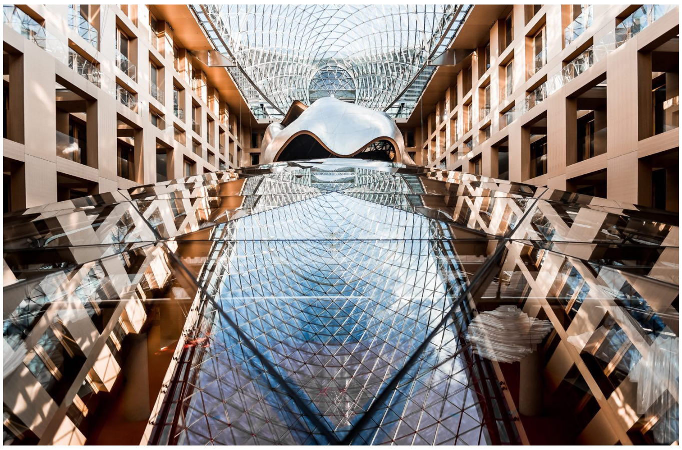


Figure 2.5.1: DZ Bank in Berlin
Source: Nancy Da Campo, Arch Daily

Figure 2.5.2: British Museum Court
Source: ARCH2O

Figure 2.5.3: New Fair
Source: Arch Daily

Rationalization

The process of rationalization is described in the Merriam Webster dictionary (2018) as "[the application of] the principles of scientific management to (something, such as an industry or its operations) for a desired result (such as increased efficiency)". While there is no universally agreed upon meaning of rationalization in architecture, geometric rationalization in buildings typically involves the process of discretizing complex geometry into a more simple geometric base that can more easily be translated into constructible elements (Stephan et al., 2004). As alluded to in a previous section, the rationalization of free-form facades typically involves breaking down a NURBS surface element into reticulated a structure. The complexity of the original geometry informs the various way in which the surface can be rationalized. The way in which the overall geometry is discretized has great repercussion on the appearance, the structural behavior and the manufacturing of the final product.

Optimization

Optimization is defined as "an act, process, or methodology of making something (such as a design, system, or decision) as fully perfect, functional, or effective as possible; specifically : the mathematical procedures (such as finding the maximum of a function) involved in this". Optimization commonly works first with the definition of optimization criteria, followed by the application of genetic algorithms to arrive at an optimal solution. Optimization criteria is either a desire minimum or maximum of a particular measurable characteristic. This can range for example, from minimizing volume/material use, to maximizing number of repetitive elements. Multi-objective optimization can balance a number of different optimization criteria and arrive at an optimal solution. There are two types of optimization prevalent in free-form facades, namely geometrical and structural optimization.

Geometrical optimization is a means of using tools to generate or rationalize the geometry in such a way that it reduces a level of complexity of the system, such as eliminating the twisting of elements or maximizing repetitive elements. More often than not, geometrical optimization is tied to maximizing the compatibility of the elements to efficient manufacturing.

Structural optimization is a means of generating or rationalizing the geometry in such a way that it corresponds to optimal load distribution. This can be done on an overall scale such as structural form-finding strategies, or on a local scale, such as applying topological optimization to reduce material of a single element based on local structural conditions. Structural optimization on its own has a tendency to generate organic forms, which present challenges to traditional manufacturing. The increasing popularity of additive manufacturing has greatly increased the potential of the application of structural optimization. Thie concept will be explored further in a later section.

A free-form facade can be geometrically optimized or not, and structurally optimized or not. A facade that is neither geometrically or structurally optimized presents the most challenging scenario to solve, as it is both geometrically and structurally complex, all the while having to fulfill the performance requirements of a building enclosure. The structural behavior of non-optimized reticulated structure, according to Reticulated Structures on Free Form Surfaces (Stephan et al., 2004), is challenging for two reasons: first, because the structural behavior of the element is generally not predictable and stresses can vary greatly in structural members, for example from pure tension or compression to predominantly bending; and second, because the structural behavior is influenced by the systems complex geometry.

Free-Form Facade Behavior

The structural behavior for a typical curtain wall is generally simple and predictable. The vertical mullions can be simplified into continuous elements. Transoms that span between mullions are either moment connected by welding, or pin connected by one of the other three connection methods. Figures 2.5.5 and 2.5.6 illustrate the various internal forces in the beams for a simple structural analysis using self weight and wind loads in karamba. Force distribution, whether the connection is pinned or welded, is planar, rational, and easily predictable with a general understanding of structural mechanics.

Free-form curtain walls (Figure 2.5.7), on the other hand, present a challenge in that neither their design or analysis are simple. There is no easy rule of thumb applicable for defining load paths and end conditions. This depends considerably on the nature of the geometry - the type of curvature of the base geometry, the level of optimization of the geometry, etc.

The process for designing free form curtain walls is generally an iterative process that requires careful consideration and a more sophisticated understanding of facade systems and structural mechanics. Engineers might begin with a simple structurally determinate model, and iteratviely fix or release connections based on applying engineering intuition to analysis results (S. Thieme, personal communication, May 05, 2018). The irregularity of the geometry in combination with the irregularity of the end conditions of the members, causes the overall structure to have rather unpredictable forces.

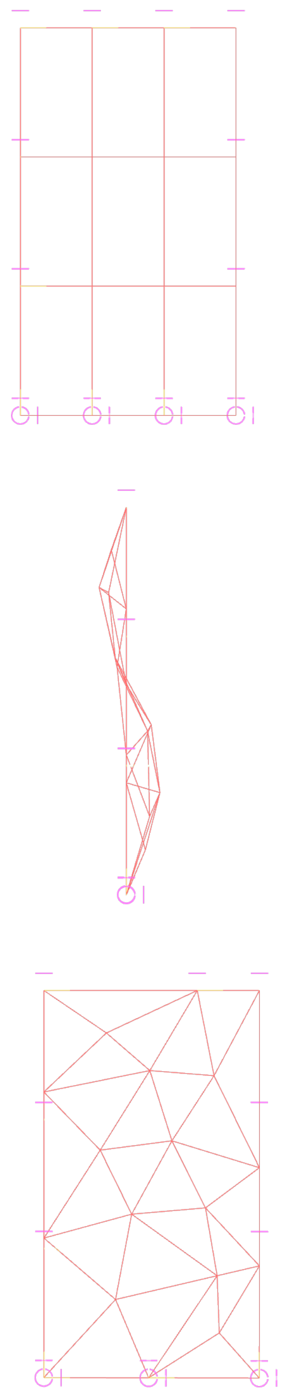


Figure 2.5.4: Hypothetical Wall Assembly Base Geometry
Source: Author

Typical Wall: Welded Connection

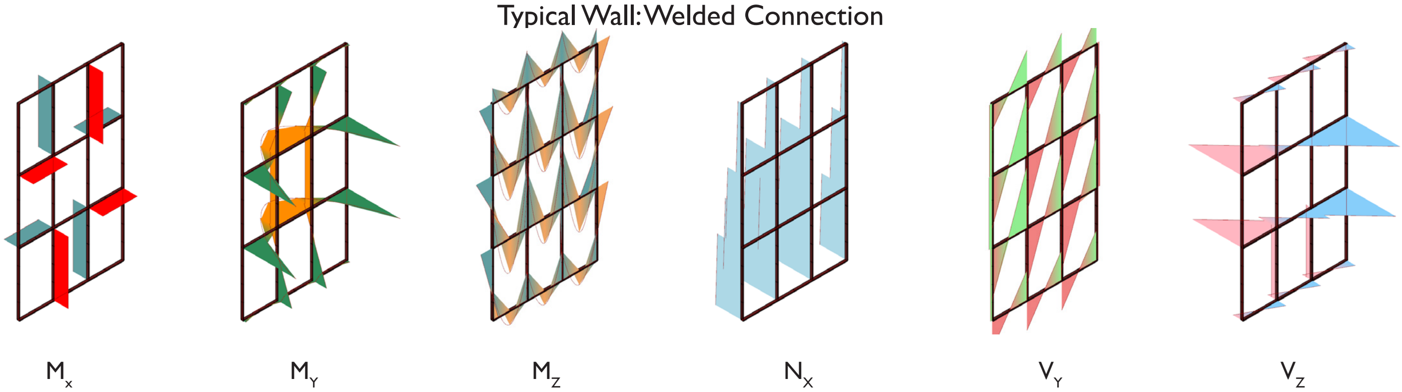


Figure 2.5.5: Karamba Analysis, typical wall with welded connections
Source: Author

Typical Wall: Pinned Connection

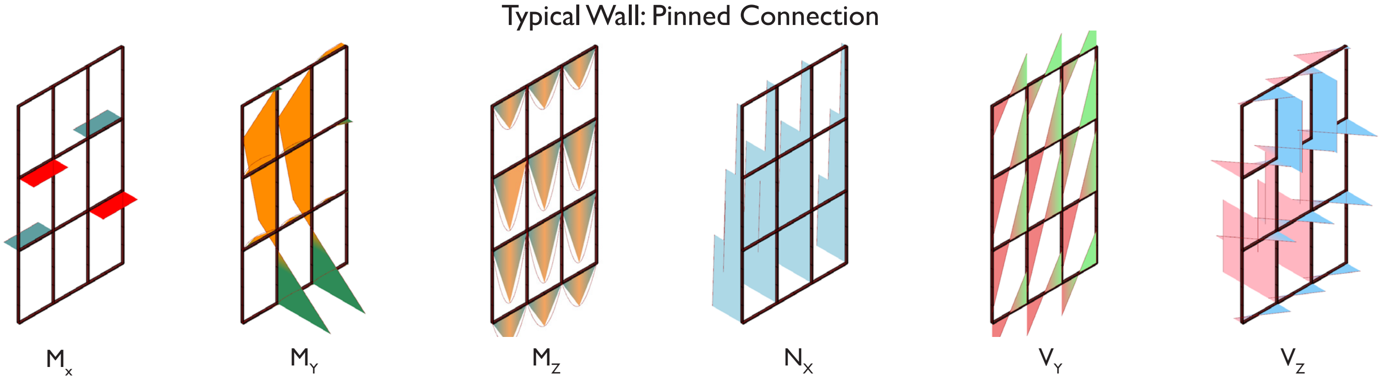


Figure 2.5.6: Karamba Analysis, typical wall with pinned connections
Source: Author

Free-form Wall: Pin-Fix

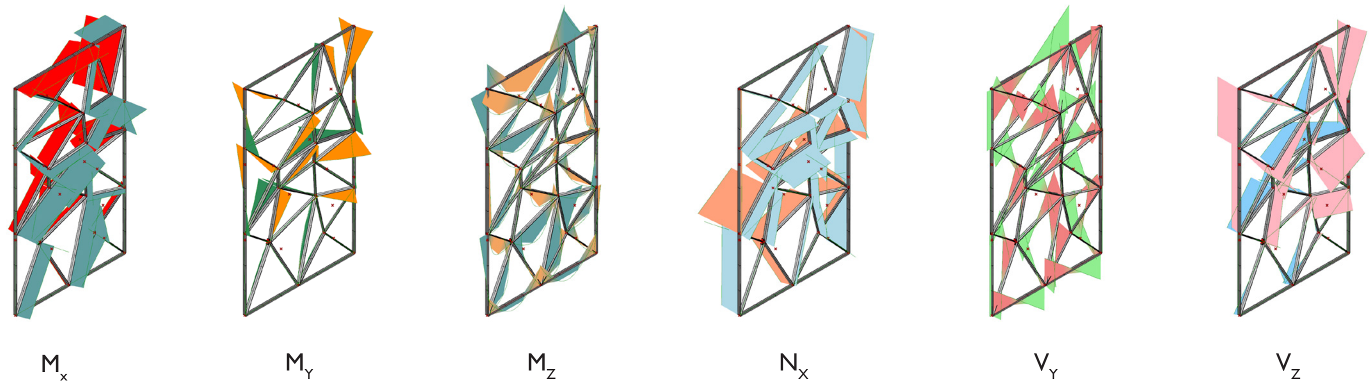


Figure 2.5.7: Karamba Analysis, free-form geometry wall
Source: Author

Free-Form Node Precedents

In "Reticulated Structures on Free-Form Surfaces", the authors illustrate a collection of single layer form nodes (Single layer free-form nodes connect members of a node from a reticulated surface, while a double layer node connects also to elements beyond the base surface such as in a space frame facade). The authors analyze each node in terms of its accommodation of local geometry, transferability of internal forces, and applicability to structurally and geometrically optimized surfaces. This analysis can be used as a basis to better understand the challenges involved in developing a free-form node.

Single-layer free form nodes can generally be divided into two categories: splice connectors and end-face connectors. Splice connectors are characterized by a splice connection between the node and the structural member running in the longitudinal axis of the structural member (Stephan et al., 2004). Splice connections can either be welded, or achieved with the use of shear stressed bolts. End-face connections are characterized by the face that the connection plane between the node and the structural member is normal to the longitudinal axis of the structural member. End face connections can be achieved by welding or with the use of tension-stressed bolts (Stephan et al., 2004).

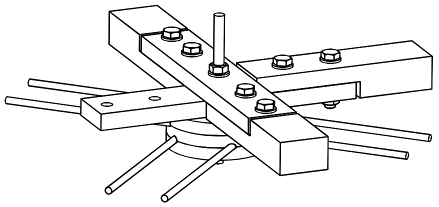


Figure 2.5.8: Splice Connector SBP-1
Source: Stephan et. al, 2004

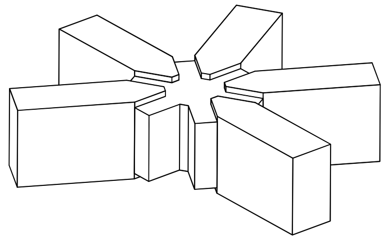


Figure 2.5.12: End-Face Connector WABI-1
Source: Stephan et. al, 2004

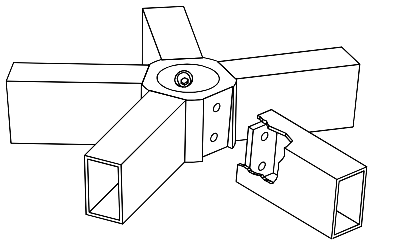


Figure 2.5.16: End-Face Connector MERO-1
Source: Stephan et. al, 2004

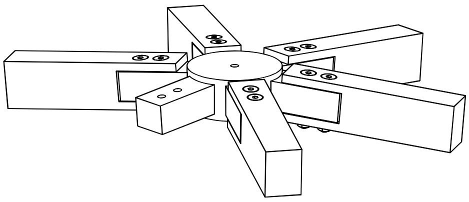


Figure 2.5.9: Splice Connector SBP-3
Source: Stephan et. al, 2004

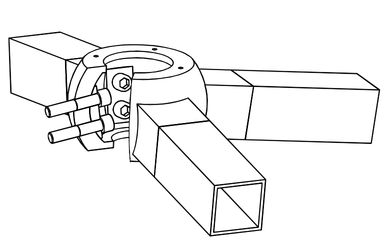


Figure 2.5.13: End-Face Connector OCTA-1
Source: Stephan et. al, 2004

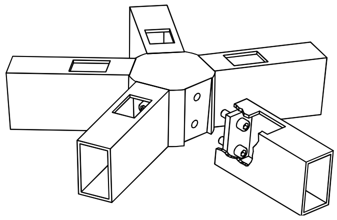


Figure 2.5.17: End-Face Connector MERO-2
Source: Stephan et. al, 2004

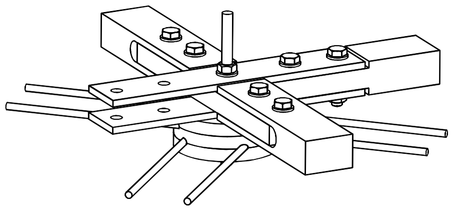


Figure 2.5.10: Splice Connector SBP-2
Source: Stephan et. al, 2004

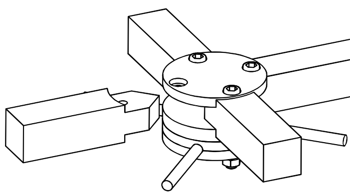


Figure 2.5.14: Splice Connector HEFI-1
Source: Stephan et. al, 2004

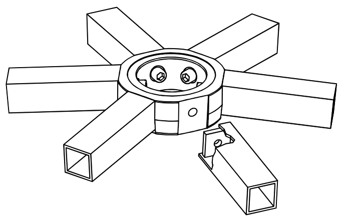


Figure 2.5.18: End-Face Connector MERO-3
Source: Stephan et. al, 2004

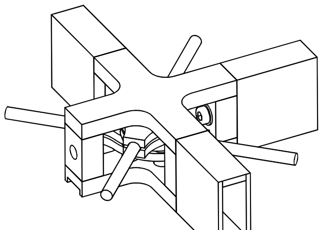


Figure 2.5.11: End-Face Connector SBP-4
Source: Stephan et. al, 2004

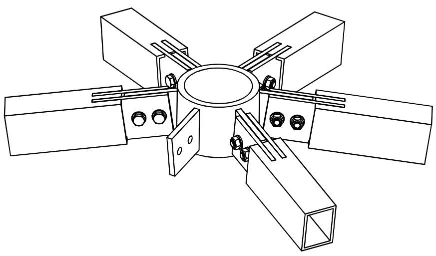


Figure 2.5.15: Splice Connector Polo-1
Source: Stephan et. al, 2004

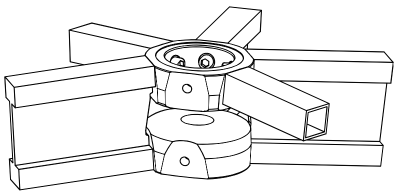


Figure 2.5.19: 'End-Face Connector MERO-4
Source: Stephan et. al, 2004

Node Connector		Accommodation of Local Geometry			Transferability of Internal Forces		Applicability
Version	Connection	Horizontal Angle U_i	Vertical Angle V_i	Twist Angle W_i	Normal Forces	Bending Moments	Free-Form Structure Type
SBP-1	Bolted Splice	+	+	O	+	O	Geom. Optim., Struct. Optim.
SBP-2	Bolted Splice	+	+	O	++	+	Geom. Optim., Struct. Optim.
HEFI-1	Bolted Splice	++	+	+	++	++	Geom. Optim., Struct. Optim.
SBP-3	Bolted Splice	++	++	++	++	++	Geom. Non-Optim., Struct. Non-Optim.
POLO-1	Bolted Splice	++	++	++	++	++	Geom. Non-Optim., Struct. Non-Optim.
SBP-4	Welded End-Face	+	+	O	+++	+++	Geom. Optim., Struct. Non-Optim.
WABI-1	Welded End-Face	++	++	+	+++	+++	Geom. Non-Optim., Struct. Non-Optim.
OCTA-1	Bolted End-Face	++	+++	++	++	++	Geom. Non-Optim., Struct. Non-Optim.
MERO-1 (Cylinder)	Bolted End-Face	++	++	+	++	++	Geom. Optim., Struct. Non-Optim.
MERO-2 (Block)	Bolted End-Face	++	+++	++	++	++	Geom. Non-Optim., Struct. Non-Optim.
MERO-2 (Block)	Welded End-Face	++	+++	++	+++	+++	Geom. Non-Optim., Struct. Non-Optim.
MERO-3 (Dish)	Bolted End-Face	++	++	++	++	+	Geom. Non-Optim., Struct. Optim.
MERO-3 (Dish)	Welded End-Face	++	+++	++	++	++	Geom. Non-Optim., Struct. Non-Optim.
MERO-4 (Double Dish)	Bolted End-Face	++	++	+	++	++	Geom. Non-Optim., Struct. Non-Optim.
MERO-4 (Double Dish)	Welded End-Face	++	+++	++	+++	+++	Geom. Non-Optim., Struct. Non-Optim.

Notation

O	Limited Suitability	**Geom. Optim.**	Geometrically Optimized Surfaces
+	Adequate Suitability	**Geom. Non-Optim.**	Geometrically Non-Optimized Surfaces
++	Good Suitability	**Struct. Optim.**	Structurally Optimized Surfaces
+++	Excellent Suitability	**Struct. Non-Optim.**	Structurally Non-Optimized Surfaces

Table 2.5.1: Applicability of Node Connectors for Free-Form StructuresSource: Stephan et. al, 2004

The analysis of the various free-form facade node precedents brings to light some of the most common issues in existing precedents for free-form nodes:

► Nodes designed specifically for applications that have been optimized, either geometrically or structurally, naturally are inferior in performance compared to nodes that are for non-optimized application. They have inferior performance requirements and therefore are not suitable for applications that do not fit their specific intended purpose. It should be noted that these systems are typically more economical (Stephan et al., 2004).

► Most splice connectors are only suited for applications that have been geometrically and structurally optimized. The two splice connections that are suited for non-optimized applications, are inferior geometrically and structurally to most end-face connections.

► Welded end-face connections are equal or superior to their respective bolted end-face connections geometrically and structurally in all instances. However, they are significantly more labor intensive.

► System solutions that offer the best performance per the results of the analysis are bulky solutions that create additional opaque areas, affecting the overall transparency and apparent lightness of the enclosure.

► Each of these solutions requires a combination of machining and high precision labor. This kind of labor is both costly and challenging, requiring more generous construction tolerances, and having a performance largely dependent on workmanship. The British museum roof, for example (Figure 2.5.2), which is a end-face welded connection, when observed, has visible welds and undesirable aesthetic properties (Figure 2.5.20). While this is forgivable given that the roof is significantly too high to appreciate the roof at a detail level, this application would be less appropriate for a ground level wall, for example where one would be close enough to see this detail up close.

► None of the available solutions provide a true continuous transition to the intersection portion of the node. The element profile section is maintained for as long as possible and cut at the ends to connect to a physically and aethetically individual element.

► Each option provides a method of fastening the mullion to the node. Almost all of these options have exposed fasteners.

► Almost all of the options create additional visual obstruction in the envelope, particularly those that make use of a spherical or cylindrical element in the center. While some of these obstructions are not significant, they do affect the overall transparency of the system and visually obstruct the continuity of the linear elements.

Figure 2.5.20: End-Face Connector WABI-1 at British Museum
Source: Stephan et. al, 2004

Schuco Parametric Facade

The Schuco Parametric facade is a unitized aluminium facade that has limited free form function. The system consists of unitized facade elements that within them have he flexibility to integrate additional depth and free-form geometry. The unitized elements can be installed in four configurations: rectangular aligned; rectangular offset, parallelogram aligned, and mirrored triangles. The unitized elements attach to one another on a single plane, and the interior components of the frame have some free-form capacity. Figure 2.5.21 from the Schuco order and fabrication manual, illustrated different geometrical possibilities for the different panels elements.

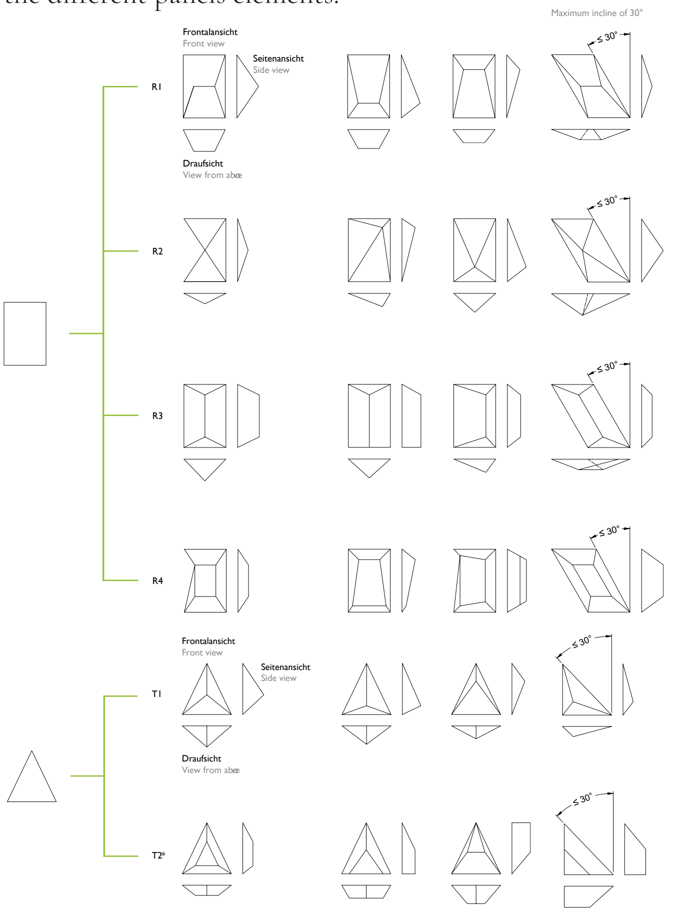


Figure 2.5.21: Schuco Parametric Units Geometrical Options
Source: Schuco

The system comes with a number of digital tools that facilitate design and support the transition into fabrication. Adding immense value to the product in the savings it provides in terms of engineering and design to fabrication labor.

The watertight free-form geometry is achieved with cylindrical elements, which do not cause problems in terms of twisting or rotation around the longitudinal axis since the mullion has no vertices to match up with other incoming members. This is efficient both in terms of aesthetic, as there is no hange in aesthetic of the section profiles around the node, as well as for fabrication, since is does not require fabricating twisted members. Rather, the challenging part of the connection is in the accurate cutting and welding of the cylindrical sections together. The system also includes a hollow cylindrical rebate insulation that can be compressed into form to provide the watertight seal. The system makes use of structural glazing (SG) as a means of providing an exterior seal and providing structural support for the glazing. This enables the system to bypass the need to generate free-form components for dry-glazed assemblies such as cover caps and pressure plates. One advantage of SG is that the visible joints between cladding elements are very small. The disadvantage is that wet-seal joints are inferior in terms of potential for circular use, maintenance and repair.

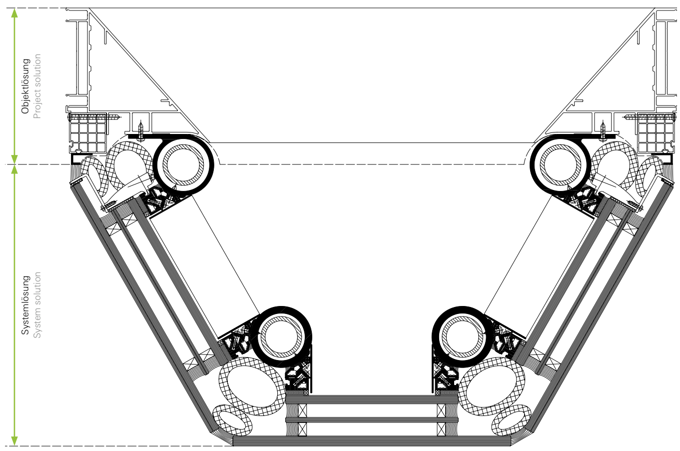
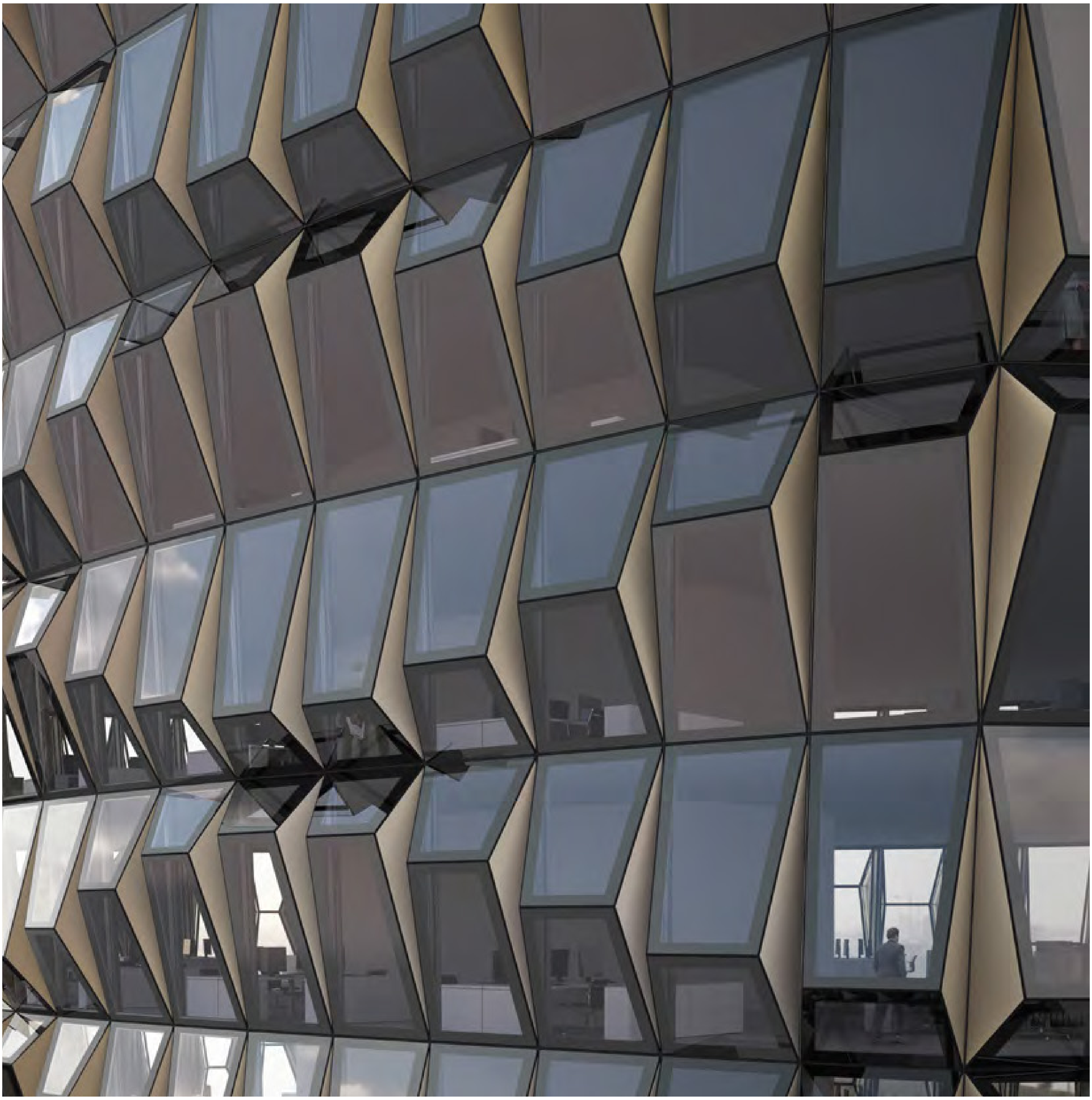


Figure 2.5.22: Horizontal Section Through Unitized Element
Source: Schuco



Source: Schuco

2.6
The Future of Curtain Wall Facades

The performance of curtain walls has steadily increased since its conception, however, existing systems still have room for improvement. While the ability to create free-form geometry is a worthwhile endeavor, it is certainly not that only goal that the industry is striving towards. With energy use and resource consumption at the forefront of all discussions concerning progress in architecture, facade research and development is in full force in both academic and professional settings. The development of new strategies to improve on the energy performance of our buildings, and the design of components of systems and components that are conducive to circular use and recycling is paramount.

In Integral Facade Construction (Klein, 2013) the author outlines a series of future challenges that facade industry professionals should strive towards. While this book was published in 2013, these challenges are still extremely relevant, and while the industry has made much progress in many of these categories, there is still much progress to be done. The increasing accessibility of rapid manufacturing presents a means of taking on many of these challenges directly or indirectly.

Klein (2013) divides general future challenges for facades into six categories: minimize embodied energy; reduce operational energy, predict facade performance; create a faster process; enable architectural possibilities; and stimulate innovation.

The use of additive manufacturing is a step in the right direction for addressing many of these challenges. While AM might not be a solution in terms of minimizing the embodied energy of a system, the advantages that it presents in other facets of improvement may well offset this disadvantage. For example, the use of additive manufacturing achieve more accurate connections with tighter tolerances in free-form facades is a step towards improving the performance of building enclosures and therefore reducing their operational energy, whilst making the facade performance more predictable. The manufacturing limitations that are lifted in additive manufacturing, which will be covered more in depth in the next section, enable the effective integration of intelligent features that can contribute to enabling architectural possibilities and stimulating innovation whilst streamlining the process for achieving them. In summation, additive manufacturing, and specifically rapid manufacturing has the potential to greatly improve the design and manufacturing of free-form facade nodes. Additive manufacturing will be studied more closely in the following section to research various ways in which additive manufacturing technology can be applied in the facade industry and in other industries.

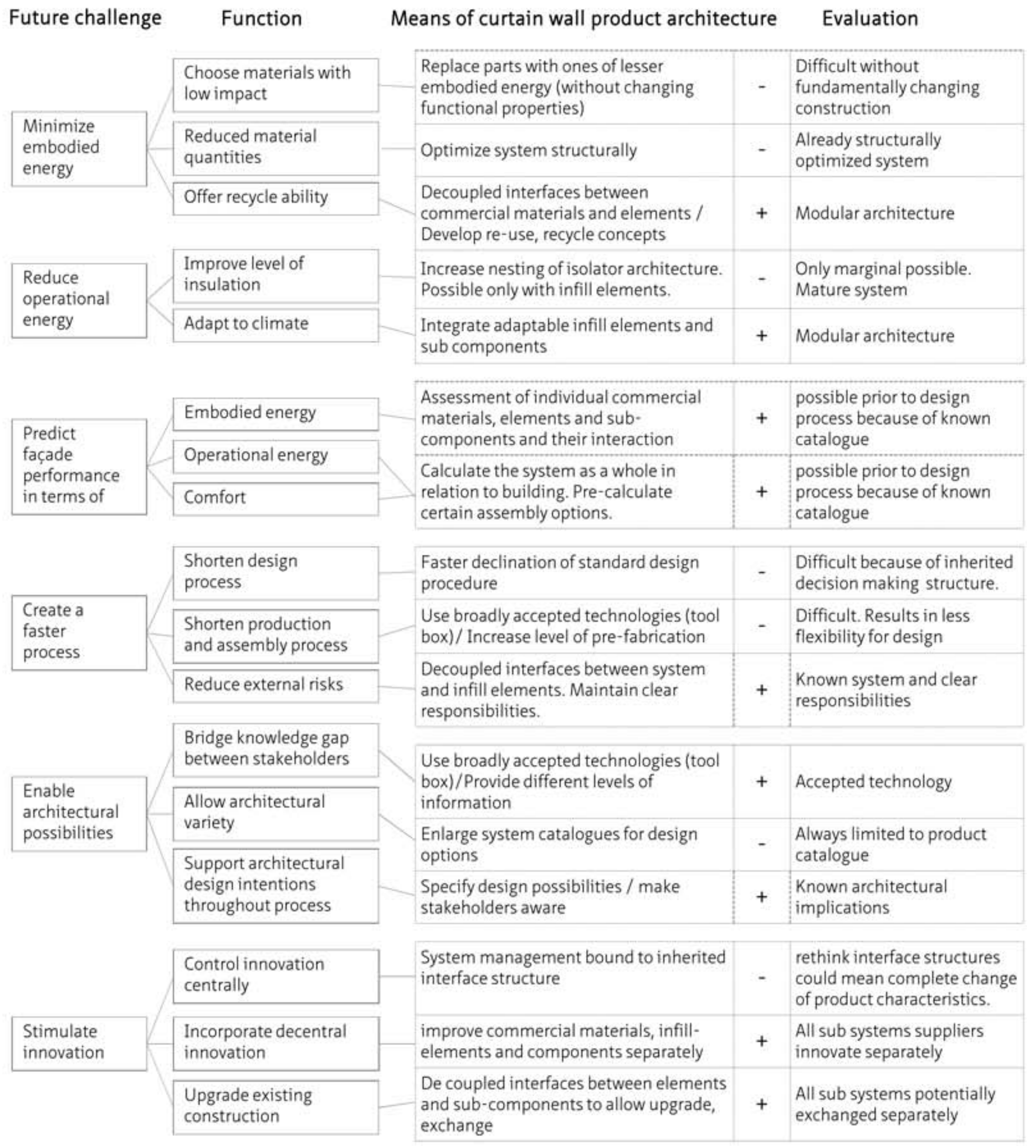


Figure 2.6.1: How curtain wall product architecture can address future challenges
Source: Klein, 2003

Summary and Conclusions on Curtain Wall Facades

Modern steel curtain wall systems stand out in the industry particularly for applications with high structural requirements. Typical application include roofs, and facades with narrow sight-lines and large glazing elements that require high mullion stiffness over long spans. The steel curtain wall industry has created quality systems that surpass the standards set out in the increasingly demanding building regulations. System components are designed to be ass efficient as possible in areas of design, manufacturing and fabrication. Manufacturing of steel, however, due to its relatively low workability, creates disadvantages in terms of geometric flexibility relative to, for example, aluminium extrusions, making it difficult to produce more optimal sections and built-in features to the main structural component. In addition to this, the tools and technology used to produce the mass-manufactured are not suitable for the production of free-form facades, which have inherent geometrical and structural challenges. Additive manufacturing has the potential overcome the limitations of traditional steel manufacturing, and enable the design of curtain wall nodes that have improved geometrical quality, assembly, structural performance, and contribute to an more intelligent and more reliable building enclosure.

03
Additive Manufacturing

This research seeks to use additive manufacturing technology to provide a cost-effective solution to the production of customized facade elements. In order to do so, it is important to establish a framework of knowledge surrounding additive manufacturing technology, the available technology and the direction that it is headed, and the impact that it has already had in various products and industries. Much of the framework presented in the following paragraphs is established by Strauß in AM Envelope, as he provides a holistic overview of additive manufacturing technology as it is pertinent specifically to the additive manufacturing of facade elements but also across other industries. This section will begin with a broad overview of additive manufacturing and gradually become more specific to its application in facades.

The term additive manufacturing as defined by the ASTM International Committee F42 on Additive Manufacturing Technologies mean the "process of joining materials to make objects from 3D model data, Additive Manufacturing (AM) as opposed to subtractive manufacturing methodologies. Usually with AM parts which are processed layer upon layer" (American Society for Testing and Materials (ASTM), 2015). This method of fabrication encompasses three primary divisions of fabrication types: Rapid Prototyping (RP), Rapid Tooling (RT) and Rapid Manufacturing (RM). The three divisions, as defined by Strauß (2013), are defined by the nature of the end use product. Rapid Prototyping produces "illustrative models for product development" while for Rapid Tooling produces tools to be used for mass production, and Rapid Manufacturing produces "ready to use products without the need to invest in tools". This research will focus primarily on RM, as the ultimate objective is to create a large number of custom elements for direct architectural application.

3.1
Rapid Manufacturing

The scope of this study is limited to the application of RM as it is considered a very efficient solution for the accelerated fabrication of custom components. While rapid tooling could also provide a potential solution for facilitating the manufacturing of complex joints, it is more geared towards repetitive manufacturing, while rapid manufacturing is more appropriate for applications of mass-customization. RM is selected as its extreme streamlining of the manufacturing process for a unique end-use product is aligned with maximizing the manufacturing efficiency of free-form curtain walls.

RM provides a number of advantages over traditional manufacturing, as well as some limitations. In order to understand the potential of additive manufacturing in addressing the free-form curtain wall challenges outlined in the previous section, it is important to understand the advantages and limitations of the technology.

RM Advantages

The advantages of rapid manufacturing can largely be divided into two categories: those related directly to the manufacturing process, and those related to the manufactured product. Within each of these categories, there are a number of advantages that relate to the physical potential brought by additive manufacturing, and other advantages more directed towards cost efficiencies.

In Deloitte's article (Michalik, Joyce, Barney, & McCune, 2014), cost savings are represented in two categories: **capital-versus-scale**, in which "AM has the potential to reduce the capital required to reach minimum efficient scale for production", and **capital-versus-scope,** in which "the flexibility of AM can facilitate an increase in the variety of products a unit of capital can produce, reducing the costs typically associated with production changeovers and customization and/or the overall amount of necessary capital". In this case, capital vs scale advantages, which refer particularly to the efficiency of AM mass customization and low-volume production are related to manufacturing, while capital vs. scope, which pertains primarily to Digitally Optimized Design (DOD), are related to the product.

Manufacturing Advantages

Deloitte's article presents advantages of additive manufacturing that pertain to the reduction of some general constraints of traditional manufacturing. The first of these is production location. AM technology typically consists of a single unit, either exposed or enclosed depending on whether the material and application require particular environmental conditions. In most cases, AM technology will come with a specification that outlines the potential build volume of the printed product. This criteria is generally limited by the bed size of the printer. These printer range from very small printers that can easily reside on a work desk, to large printers such as the Winsun concrete deposition 3d printer that has a build volume of 2,400 m3. Other technology, such as the MX3D pedestrian bridge, printed with Wire and Arc Additive Manufacturing (WAAM) technology, (Figure 3.1.1) strives to have theoretically infinite build volume by providing a mobile printing platform. Within the range of scale of the various AM technology from which the industry can choose from, almost all of the available technology is significantly smaller than the space required for traditional mass manufacturing. This means that designers and fabricators can often take advantage of AM technology from their offices without having to have access to immense manufacturing warehouses. This presents an advantage to industries that seek to produce certain products in space constrained settings, to entrepreneurs and small businesses that do not have the capital for leasing large production spaces, and to niche operations such as space missions, where space (inside the shuttle, obviously) is limited and the product demand is unpredictable. Here,

Figure 3.1.1: MX3D Bridge
Source: MX3D.com

additive manufacturing is an opportunity to produce repair parts as needed without the need to travel with an inventory of spare parts. In the case of the MX3D Bridge, the mobility of the printer means that the object can be printed on-site. Even in a mass-manufacturing industrial setting, in an operation with a limited number of machines in a manufacturing line, a single AM machine could take up a small corner of a working factory supplementing the demand for custom pieces without interrupting the steady flow of mass manufactured products. Ultimately, the relatively compact size of additive manufacturing tools create an unprecedented amount of freedom in not only how, but also where we are able to produce end-use products, enabling design teams to produce things in the most logical, efficient and/or economic location. Another related advantage of its digital nature is that objects can also be printed remotely, potentially reducing both energy and costs related to transportation. Once additive manufacturing technology advances and continues to become more common and more accessible, this capability will become increasingly advantageous.

Capital vs. Scale

One of the most important advantages of rapid manufacturing is the cost reduction that it enables in low-volume production. These cost savings run across the entire fabrication process from design through to final product, and are achieved through means of raw materials savings, advanced technology and reduced labor.

Material

Additive manufacturing enables cost savings in material savings due to the additive nature of the manufacturing process. This model essentially eliminates scraps that subtractive manufacturing produces, and eliminates the need for tooling material such as producing moulds or dies. In the case of technology such as selective laser sintering, unused powder is collected and reused in the next application without need for any additional processing.

Tools and Equipment

Traditional manufacturing requires the use of tools that are used to perform a series of operations on raw materials, or on basic material products such as bars, coils, or plates. Many of theses operations require machines whose capability to produce different geometries is dependent on costly components such as molds and dyes. In manufacturing cold roll steel sections for curtain walls, for example, the manufacturing lines uses hundreds of rollers to roll steel coils into the desired shape - each coil costing upwards of 130,000 CHF (Hyseni, 2018). For mass manufacturing of standard sections, this type of investment is worthwhile, however for unique applications, in most cases it is not. While RT is a method of making tool production more cost effective, RM removes the need for these expensive tools altogether.

Time

As its name suggests, cost savings are in many ways achieved in rapid manufacturing by the streamlining of manufacturing processes. In traditional manufacturing, a significant amount of time need be allotted to fabrication documentation (prints & layouts), tool programming and setup, tool design, and tool manufacturing. In rapid manufacturing, much of these time consuming steps are eliminated or reduced: Only a single digital model is necessary for fabrication rather than a number of prints and layouts; this single model can be interpreted by intelligent software and produced by a single additive manufacturing machine rather than a number of machines having to be adjusted and programmed for a sequence of specific tasks, as well as the number of laborers required to do quality control and facilitate transitions between process steps (Wu, Wang & Wang, 2016). The streamlining of the fabrication process produces cost savings in significant ways by reducing labor, machining time, tooling energy, reducing lead times and maximizing production which increase profit.

It is important to note that this advantage concerns mostly the manufacturing of complex components that require extensive work within the means of traditional manufacturing. While AM will likely not compete with traditional manufacturing for simple products like extruded or cold-rolled sections, it has proven to be a valuable time saver in more complex applications.

Digitally Optimized Design

Digitally optimized design simplifies the manufacturing process of objects with additive manufacturing, enabling the design of a number of features that were either impossible or too costly using traditional manufacturing methods. In AM Envelope (2013), the author draws on the example of traditional moulding methods and parts, which clearly define the limits of the end product, where "technical restraints limit the freedom of design in terms of demouldability, homogeneous wall thickness, and integration of slide feeds or split lines". These limitations, depending on the selected method of AM, do not represent significant limitations in additive manufacturing. Other complex geometrical feats are also achievable such as internal passageways and undercuts (Wu et al., 2016), "integrated joints, articulating bodies inside enclosed envelopes ('sphere in a sphere'), or contour-conform channels (to cool tools during mass production)" and physical ones such as variable material densities (Yang et. al, 2017). While some of these type of characteristics were possible with complex sequences of traditional manufacturing, they came with significant cost increases that often required the products to be less efficient in favour of economic manufacturing.

The newfound accessibility of these characteristics allow us to achieve optimized design that achieve features such as "minimize [use] of metal, optimize strength, or extend functionality" (Milewski, 2017). Biomimicry, the concept of "imitation of natural biological designs or processes in engineering or invention" (Biomimicry. n.d.) is a trending subject amongst architects and engineers. As we seek to replicate the advantages of certain natural phenomenons, one will be quick to recognize that these are in nature very seldom achievable in their full potential with traditional manufacturing techniques. Additive manufacturing enables the easy and economic application of biomimetic principles that in many cases traditional manufacturing did not allow.

Some rapid manufacturing methods also enable the consolidation of a number of components into a single printed integrated element. The integration of assemblies is a feature that creates labor costs- savings, thus increasing the value of the product. This type of integration is not limited to static elements. Kinetic elements, such as functional gear bearings can be produced in a single print from a 3D printer.

Another very significant advantages that comes from digitally optimized design due to its digital nature, is the non-traditional sourcing of design information. A relevant examples of this sort is 3d scanning. 3D scanning has potential that is being investigated across industries. In medicine, the use of 3d scanning is a means of collecting physiological information that enables relatively quick and easy custom-fit AM medical apparatuses such as implants and prosthetics. In architecture, 3D scanning is potentially a way to build custom curtain wall support structure that accommodates for concrete construction tolerances. In the automotive industry, it can be used to replicate and rebuild parts for classic cars. Other sources of digital information includes data from digital tools that can range from environmental data, to internal stresses, to loads from computational fluid dynamic analyses.

Capital vs. Scope

Capital-versus-scope method relies on innovation of the product itself rather than the way that it is manufactured. Savings are made possible digitally optimal design (DOD), namely products intended for end-use on AM systems. In the article by Deloitte (Michalik et al., 2014), the authors are quoted in saying that "since the ability to manufacture what was previously impractical or impossible suggest that design, too, can strive for what was once impractical or impossible". Digitally optimal design enables designers to create revolutionary objects unencumbered by the limitations of traditional manufacturing.

These objects have the potential to reduce costs in many ways. For example, one can reduce material cost through optimization, or assembly costs by redesigning assemblies as homogeneous elements. Digitally optimized design (DOD) encompasses an almost endless range of possible applications. It enables designers to create products of unprecedented intelligence that in addition to benefiting all of the cost-saving measures mentioned to-date, also potentially increase the value of the end-product through intelligent design.

RM Limitations

The advantages of additive manufacturing on traditional manufacturing are plenty. Additive manufacturing techniques resolve many of the shortcomings and limitations of traditional manufacturing techniques. Rapid manufacturing itself however, it should be noted is certainly not without limitations of its own. This section will include limitations of rapid manufacturing in general as well as specifically metal RM.

Constraints for Cost-Effective Manufacturing

While, as previously stated, the rapid manufacturing can provide a cost-saving measure for certain applications, namely mass customization and geometrically complex applications, it is almost exclusively economically feasible for these applications. The conclusion to be derived from this particular set of limitations is that perhaps, at least in the foreseeable future, rapid manufacturing is in many cases not to be seen as a replacement of traditional manufacturing techniques but as a supplement for products that can most benefit from the allowed complexity and customization of RM techniques.

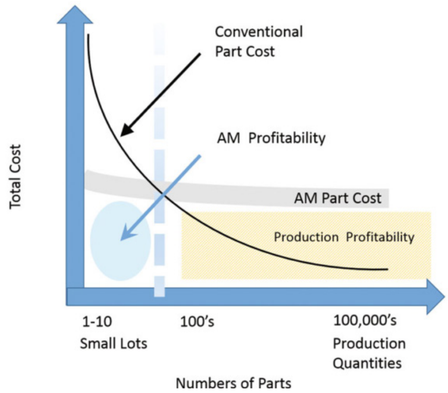


Figure 3.1.2: Break even analysis (BEA) b/o Deloitte approach Source: Milewski, 2017

Metal RM: Fabrication Cost

It should be taken into consideration that while additive fabrication has made a popular name for itself as being simple and economical, the reality is that, particularly the rapid manufacturing of metals, is still a costly process. Figure 3.1.3 illustrates a number of factors that affect the cost of a metal AM product. These factors affect the cost of a given print. In addition to these costs, it is also important to consider the costs related to the infrastructure needed for metal 3D printing. Professional commercially available metal 3d printers range from hundreds of thousands to millions of dollars (Milewski, 2017). There are also additional recurring costs and non-recurring costs involved in becoming equipped for the rapid manufacturing of metals including but not limited to machine costs, consumable costs, building retrofit costs, and machine operating costs. For industrial applications, it is not uncommon for even just the non-recurring costs, namely the equipment costs and necessary building retrofits including "Shop air" and electrical upgrades, to run up to hundreds of thousands or millions of dollars (Milewski, 2017)

Control Environment

DMF methods are created by melting (or sintering) materials at a high temperature to bond particles to adjacent ones. This process, due to the relatively high melting point of metals, means a high concentration of heat in the printing bed. The temperature of the environment and of the metals must be highly controlled in order to have a successful print. In order to avoid the oxidation of the material during the printing process, the material fusing temperature should be held at just below its melting point (Wu et al., 2016). If the resulting heat is not exhausted and the temperature in the printing environment is too high, the product risks forming melting bath accumulations that cause deformations such as material adhesion and other defects (Strauß (2013)). According to Strauß, in almost all DMF methods, the contour of the model serves as a heat conducting element, while the support structure is used to direct waste heat.

Incorrect temperature regulation can also cause material tension that risks manipulating the part in an undesirable way. For example, in the case of powder bed processing, can cause material tensions that risks detaching the part from the base plate or repositioning the part in such a way that the whole manufacturing of the part needs to be aborted (Strauß (2013)). The process of moderating temperature throughout the printing is more sophisticated and requires more "intensive data preparation" than with plastic models.

Structural Behavior

Each different method for the rapid manufacturing of metals has a different effect on the way that the material particles bond to one another, ultimately affecting the strength of the manufactured part. In many applications of rapid manufacturing, particularly of metals, strength is of crucial importance. The overall strength of an alloy is defined by its micro-structure, which is a "result of its inherent chemistry, manufacturing process, and heat treatment" (Milewski, 2017). Depending on the RM method, one may be able to select specific printing parameters that can increase the strength of the element. For example, similar to extrusion based processes one can choose to specify or randomize the orientation of the layer in order to eliminate preferential grain growth and minimize residual stresses (Gibson et al., 2015). However, in many application this requires critical consideration.

Part Quality

The successful printing of metal part via RM is dependent on the proper selection of RM technology, and the proper settings of parameters based on both the geometry and material in question. Without taking these things into consideration, each piece risk deformation and other defects. While innovation in RM technology is moving in a direction that renders the entire process as intelligent and user-friendly as possible (Milewski, 2017), and the creation of materials that are reliably applicable without support structures (Strauß (2013)) the current state of the industry requires much trial and error before achieving successful outputs (Milewski, 2017). Especially for rookies in Metal Rapid manufacturing, time for multiple printing attempts should be built into the delivery process. (Strauß (2013))

Time

AM is a potentially effective way of reducing the production time for fabrication. That being said, as the manufacturing of products gets smarter, so do the product themselves, and some of the time savings that are accomplished in manufacturing products are just repositioned in the design phase of the project. While perhaps this additional time spent on optimization and engineering is offset in the increase in value of the product, it is still worth noting that the design of intelligent products that take advantage of the various benefits of additive manufacturing and digitally optimized design can be a time intensive endeavor.

In his description of the process for the Nematox node in AM Envelope (2013) , the author describes 120 hours of CAD engineering in order to create a "print-proof .stl file". Some common software applications enable the fast tracking of certain processes such as BIM exports for 3D printing, however these processes still cost time (BIM facilities and 3D Printing).

Standardization

One of the biggest social obstacles that rapid manufacturing faces on the way to common use in the architectural industry is that it lacks the level of study and understanding that result in approved standardized products and methods for certified application inbuilt projects. According to Milewski (2017), in order to realize the full potential of metal AM, a thorough understanding of good design as well as process control is necessary. Milewski lists material properties, product consistency, process repeatability and process transportability as several factors limiting the standardization and certifications of these methods for critical applications.

There are many associations that are working towards the standardization of additive manufacturing. Amongst these, the German 'Verein Deutscher Ingenieure' has published Norm 3404 in 20019 which regulates the terms and applications of Additive Fabrication including"field-proven tips and recommendations". The American Society for Testing and Materials (ASTM) has a number of technical committees dedicated to developing standards for Additive Manufacturing including general standards for metals and plastics, as well as specified industry committees such as aerospace and aviation. As of yet, there is no official ASTM committee for additive manufacturing in architecture. (ASTM International). While these standards mark improvement in the standardization of additive manufactured products, there is still much project to be made before the practice is commonly accepted in architecture.

CAD Limitations

The potential of additive manufacturing technology is connected to that of the CAD/CAM digital tools that generate and manage the geometry for fabrication. In additive Manufacturing Technologies (2017) the authors outline a number of limitations of CAD technology that directly affect the potential of additive manufacturing. This include the inability to support models with a large number of features (potentially hundreds or thousands), the inability to specify material compositions, the inability to represent physical properties, and in some instances limitations in geometrical freedom.

Method Specific Limitations

In addition to the general limitations of rapid manufacturing, each method of additive fabrication has its own limitations specific to its material nature and technology that influences whether or not it is an appropriate method of manufacturing for the application at hand. These will be elaborated on in the RM method data sheets.

3.2
Design for Additive Manufacturing

Traditional manufacturing methods have led to the development and common use of Design For Manufacturing (DFM) principles. These principles, developed for the purpose of creating product design that minimize, manufacturing and assembly difficulties and costs (Gibson et. al, 2015). While DFM principles have been very effective tools for creating efficient designs within the limitations of traditional manufacturing methods, the proper application of these principles requires an in depth knowledge of "manufacturing and assembly processes, supplier capabilities, material behavior, etc." (Gibson et. al, 2015). DFM principles can be learned through published guidelines such as the Handbook for Product Design for Manufacture, and the Boothroyd and Dewhurst toolkit, s well as through practical knowledge and best practices passed on in industry.

Design for Additive Manufacturing (DFAM) as opposed to DFM, is significantly less hindered by geometrical limitations, and therefore shifts the focus of the manufacturing objective from manufacturing limitations to design functionality

(Yang et. al, 2017). In DFAM, it is the design functionality that drives the material and process selection rather than the way around. Figure 3.2.1 illustrates a number of potential opportunities that additive manufacturing can present to a given application, and causal connections between these opportunities. The diagram outlines levels of complexity achievable with additive manufacturing, including form complexity, functional complexity, material complexity and hierarchical complexity, and links them to a number of design cost-opportunities in increased product value, cost reduction, indirect value proposition, sustainability improvements, and improved manufacturing time. These categories, and the opportunities categorized within them, can be applied individually or in combination. Good DFAM can apply any number of these opportunities to arrive at an optimal design. It should be noted, however, that DFAM is not without its limitations, many of which are method specific and will be discussed more closely in the RM methods section.

The DFAM factors as shown in Figure 3.2.1 provide opportunities to affect the production cost and product value through design. However, in addition to this, it is important to also consider in DFAM practical factors to do with printing and printing parameters, including material Type; Material Vendor; Part and Support Volume; Z Height; Build Parameters; Machine Run Time and Operating Costs; Secondary Processing; Post Processing and Finishing; Build Volume Nesting; as well as the labour costs related to design, engineering, and post processing.

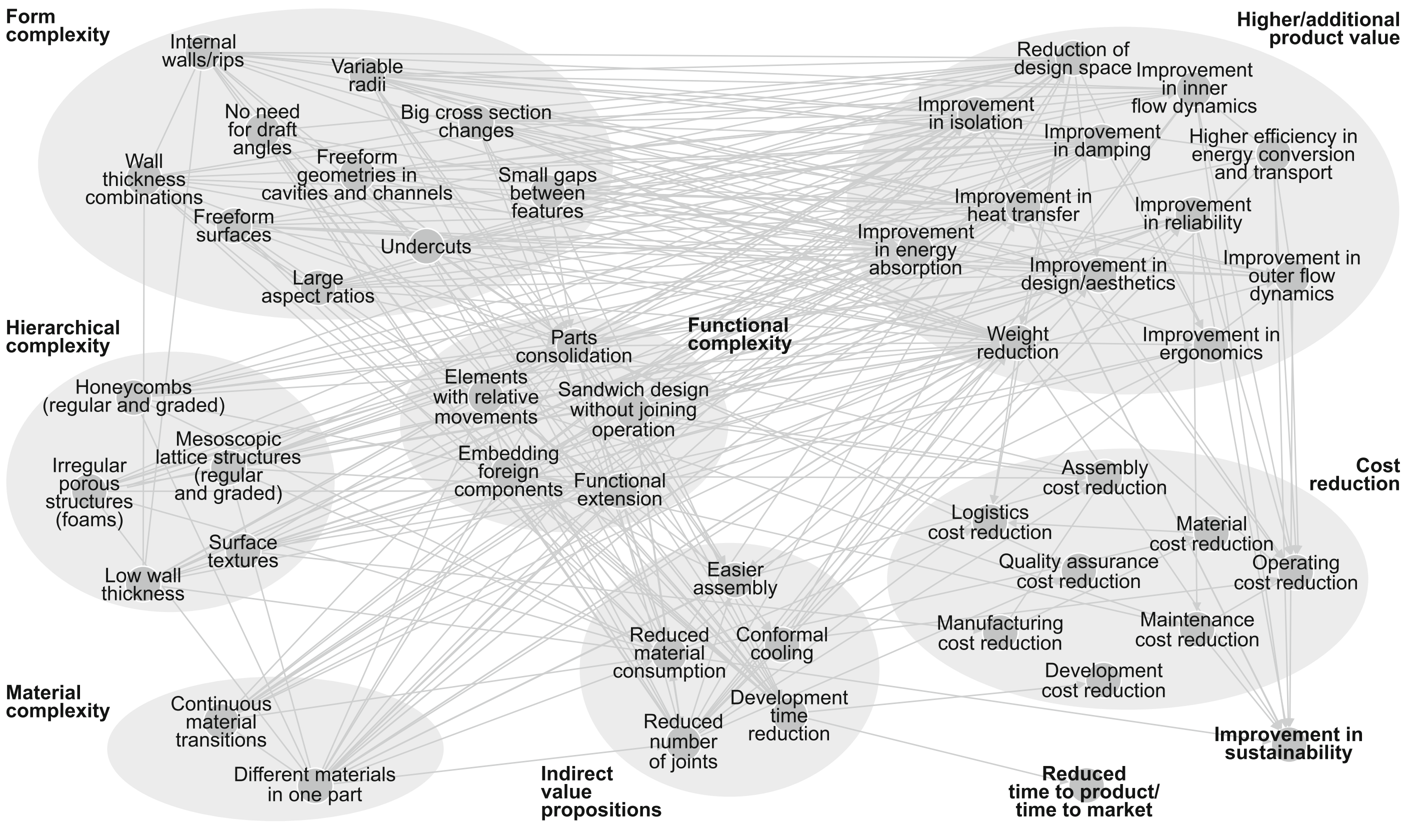


Figure 3.2.1 Semantic network of AM design potentials
Source: Kumke et al. *(2018)*

3.3
Structural Optimization

The term structural optimization is typically used for the optimization of engineering structures for "improved strength or stiffness properties and reduced weight or cost" (Haftka & Sobieszczanski-Sobieski, 2016). The optimization of structures based on Finite Element models started as early as the 1960 by L. Schmit. In the early stages of structural optimization, the process was focused on the optimization of dimensional variables such as cross sectional areas and plate thicknesses (Haftka & Sobieszczanski-Sobieski, 2016), also known as free-size optimization. The development of structural optimization has improved much since its conception largely due to computational advances. While free-size optimization is still very prevalent, other methods of optimization have surfaced more recently that enable more sophisticated modifications to the design geometry. The increasing accessibility of additive manufacturing has had a great effect on the increased popularity of structural optimization, since the optimized results, which are often complex and/or organic forms are no longer limited by traditional manufacturing methods.

Structural optimization can be applied either at an assembly level or local level. At the assembly level, the base geometry or rationalization of the entire structural assembly is optimized. This can be for example structural form-finding, or finding the optimal location of structural members in a reticulated structure. At the local level, the level with which this research is concerned, a single component is optimized.

Most structural optimization tools provide options from three types primary categories of structural optimization: size optimization; shape optimization, and topological optimization. While each of these methods gives different results, they are based on the same basic steps:

1. modeling/definition of base geometry (design space and non-design space)
2. definition of loading and support conditions
3. definition of optimization objective for example maximizing stiffness, minimizing weight, etc.
4. optional definition of additional constraints, for example displacements, stresses, etc.
5. run optimization to obtain result

The following is a short description of the main methods of optimization as outlined in Additive Manufacturing Technologies (2017).

Size Optimization

Size optimization is the defining the value of dimensions (Gibson et al., 2015). It can be used to achieve objectives including "the minimization of maximum stress, strain energy, deflection or part volume or weight" (Gibson et al., 2015). In size optimization, the output is geometrically predefined, for example the optimization will define the radius of a circular HSS, but the result will always be a circular HSS. Size optimization can be applied at the large scale, such as structural elements, or at the small scale such as internal lattice members. In size optimization, there is no need for a change in the finite element model of the structure (Haftka & Grandhi, 1986).

Shape Optimization

Shape optimization is an optimization route where there occur modifications to the shape of the input geometry. In Additive Manufacturing Technologies (2017), the authors describe shape optimization as a generalization of size optimization, where its the shape of the primary geometrical elements is optimized to achieve similar objectives and constraints.

Figure 3.3.1 Shape optimization: (a) initial design; (b) final design
Source: Haftka, R. T., & Grandhi, R. V. (1986)

Topology Optimization

Topology Optimization is determining the "optimum material layout for a given design space which takes into account any number of design constraints" (Altair). The optimization process defines within the design space the element density as presence or absence of material. This type of optimization enables simulation driven design, in which CAD and CAE are used simultaneously rather than sequentially (Altair). This type of optimization can replace iterative design/testing to achieve structural performance. Topological optimization can be applied in either 2D or 3D. Particularly in cases of 3D optimization, the results often yield complex and/or organic geometry that cannot easily or effectively be manufactured with traditional manufacturing methods, and relies on additive manufacturing technology.

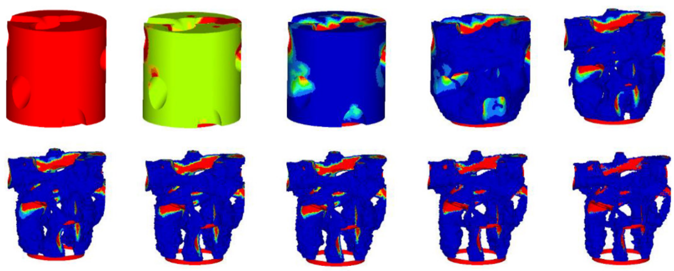


Figure 3.3.2 Topology optimization process of the node in OptiStruct
Source: Galjaard, Hofman, Perry & Ren (2015)

3.4
Rapid Manufacturing Methods

In AM Envelope (2013), the author states that the principle for all additive manufacturing is the same, namely that a special computer software slices the breaks the Computer Aided Design (CAD) model down into layers, whose contours and fillings are processed consecutively. While the basic principle remains the same, it has evolve into a myriad of printing methods that vary in defining characteristics such as base material, material form, binding method, energy form and specific tool use, and also more practical measures such as cost, potential print size, and potential safety factors that also need to be taken into consideration when selecting a printing method for a particular application.

Selecting an RM Method

The rapid manufacturing of metals typically consists of the melting of materials by applying heat (Strauß, 2013). This heat can be applied by different sources including laser or electron beam. The origins of metal additive manufacturing has its origins in Powder Metallurgy, laser and weld cladding, and in polymer 3D printing (Milewski, 2017). The degree to which each of these plays a role in specific metal AM methods varies.

There are various ways of classifying the various methods for additive metal manufacturing. For the purposes of this paper, the classification used by Milewski in Additive Manufacturing of Metals is used as it offers a neutral and informative primary classification based on the material

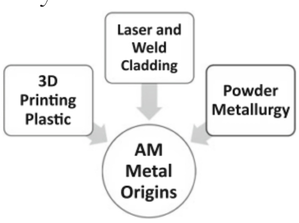


Figure 3.4.1: Origins of AM metal processing technology
Source: Milewski (2017)

feed method. In this classification method, most popular metal RM methods can largely be subdivided into two overarching categories: direct energy deposition (DED), and powder bed fabrication (PBF), each of which is further subdivided based on the strategy for melting the metal base material. The four major categories for metal AM as stated by Milewski are laser based powder bed fabrication process (PBF-L), Laser Beam Directed Energy Deposition Systems (DED-L), Electron Beam Powder Bed Fusion Systems (EB-PBF), and Electron Beam-Directed Energy Deposition Systems (EB-DED). Within each subcategory, various methods are available, characterized by thing such as changes in laser power, laser spot size, laser type, material delivery method, inert gas delivery method, feedback control scheme, and/or the type of motion control utilized (Gibson et al., 2015). Beyond the major categories, there exist other standalone, proprietary, and innovative methods for metal rapid manufacturing.

When selecting the appropriate method for a particular application, there are many factors to consider in selecting the appropriate RM method. In Materializing Design by Larry Sass, and Rivka Oxman, (2016) the authors describe the necessity that a component design comply with the 3D printers capability and raw material performance. In keeping with this, there are several factors , physical factors and practical factors, to consider in choosing the appropriate method of additive manufacturing. Physical factors include the following: material compatibility, structural behavior, layer thickness, surface quality, and part size. In addition to this, selection must be made based on practical factors such as cost, time, level of post-processing, and service availability (Milewski, 2017). Following is an elaboration on some of the above considerations.

Material compatibility

The method selected for rapid manufacturing must be suitable to the material that is being processed. Physical properties of the material such as its melting point and malleability as well as more practical properties such as the various forms that the material can come in are factors that will affect the additive manufacturing method. “A family tree of AM Technology” by Strauß (Figure 3.4.1) links the various additive manufacturing methods to whether they can be applied to polymers, metals, or other materials.

Figure 3.4.2: Family tree ‘AM methods’
Source: Strauß (2013)

Materials can also be modified to improve their characteristics specific to additive manufacturing techniques. For example, in “A critical review of the use of 3D printing technology in the construction industry” the authors describe the various ways in which concrete can also be optimized for 3D printing by modifying its bonding and “extrudability” by changing the sand/binder proportions and other admixtures, which ultimately improved the stiffness and compressive strength of the 3D printed building piece.

Structural Behavior

The micro-structure of additively manufactured components varies from traditionally manufactured processes, as well as between the various additive manufacturing methods themselves. Properties of the base material, the melting/sintering and solidification strategy are amongst the parameters that can affect the structural behaviour of a component at the micro-scale. The change in the micro-structure of the component inherently changes the structural behaviour of the part, which can be an advantageous or disadvantageous feature. In Additive Manufacturing Technologies (2017), the authors describe applications in which LENS technology controls the size and cooling rate of the melting pool to alter the nanoscale (precipate distribution) and micro-scale (secondary particles) yielding a product with varying material and mechanical properties. Such control over the behaviour of the final product requires an in depth understanding of the technology and of metallurgy, and is not typical in most AM applications. That being said, the development demonstrates another level of freedom that AM offers over traditional manufacturing methods.

Layer Thickness

Layer thickness is defined by the resolution of the AM system used (Strauß, 2013). The thickness of the layers will have an effect on the overall printing time of a manufactured product because it will increase or decrease the number of layers that the tool with have to print. In a similar way, also depending on the RM method, it will affect the structural performance of the product because it will define the total area of layer bonding. Finally, the layer thickness has a significant impact on the surface quality of the final product, as most methods will generate some sort of stepped surface to the layered nature of most RM techniques, and the thickness will define the resultant length of the run in each step.

Part Size

Various methods of RM have different economic part sizes. This is dependent on two main factors: the quality of the control environment, and the printing equipment. Processes the work with metal powders, for example, typically need a highly controlled printing environment for the quality of the print and for safe printing, which requires a fully enclosed build chamber. For these methods, printing is typically only economical in small part sizes. Printing methods such as Direct Metal Deposition, which often make use of multi-axis Computer Numerical Control (CNC), often do not require such a highly control environment and therefore can have an open build chamber. In this scenario, part size is less limited by the build environment, but on the reach of the machine.

Time

The time needed to complete an end-use product with the use of rapid manufacturing can take anywhere from several hours to days (AM Envelope). The time is largely dependent on several factors, namely the speed at which the tool operates and the surface area it is capable of treating at once, the rapidity and frequency of the curing process, and the quantity and complexity of the various steps involved in the entire process.

Post-processing:

Some methods of additive manufacturing require the post processing of the additively produced product, particulalry in application with a low surface quality. These post-processing tasks should be taken into consideration as they can add to the overall processing time and complexity, and perhaps require other additional expensive tools and machinery. This can include tasks such as “removal from support fixings, surface cleaning, removing of uncured metals, infiltration, and others” (AM Envelope)

AM method comparison

The following is an overview of common PBF and DED methods, two of the leading methods of metal additive manufacturing, for comparison, as well as a selection of recently developed technology. The overview includes inventory of advantages and disadvantages of the various methods. Information in this section is are primarily taken from Additive Manufacturing of Metals by Milewski unless otherwise noted. It should be noted that research surrounding RM is continually advancing, and the capabilities of the various methods are continually increasing, and that additional methods are being developed.

Powder Bed Fusion (PBF)

ASTM Categories:	PBF-EB, PBF-L
Specific Methods:	PBF-L: direct metal laser sintering (DMLS), selective laser melting (SLM) PBF-EB: electron beam melting (EBM)
Applicable Materials:	Primarily for metal powders, but can also be used for polymers, ceramics and metal matrices

Titanium hip implant printed with EBM technology
Source: 3dsystems.com

Process

In all powder bed applications, an energy beam (laser or electron beam) is directed at a powder bed to fuse a layer of powder based on a cross section of a digital model. The powder bed as well as the part are subsequently lowered and a new layer of powder is coated using a roller or blade. This powder layer is fused in the same way as the previous and this sequence continues until the part is printed. Special considerations for all PBF methods include the raster pattern which has strong effects on the quality, micro-structure, and defect structures of material in the completed part (Li et al., 2017).

Recent Innovation

- ► Increased processing speed by powder heating
- ► Higher purity inert gas supplies for reactive metals
- ► Use of inert gas for accelerated cooling
- ► Ability to operate in fully unattended mode
- ► Real time powder collection

Ongoing Innovation

► Steadily improving build speed, dimensional accuracy, deposition density and surface finish

► Replacement of current STL file format with new 3MF to address some of the limitations of the STL file format.

PBF Advantages

+ STl style file format is usable throughout a wide range of CAD software. This file format enables the user-friendly fixing, editing, slicing and preparation of digital models for 3D printing.

+ Enables the production of multiple parts or multiple instances of the same part in single print offering potential high build volume utilization. This can be facilitated by software that optimizes part configurations for maximized production.

+ Tight tolerances that enable complex geometry compared to DED methods. Capable of geometry such as complex shells, internal lattice structures, internal cooling channels, or complex superstructures. These features can potentially minimize use of metal, optimize strength or provide increased functionality.

+ Excess material powder does not experience significant material stressing due to heating and therefore is reusable. This reuse, however, is not eternally cyclical. There is currently research underway to determine how often specialty powder can be reused in AM PBF methods before it undergoes significant enough changes to its physical properties to render its use unacceptable.

+ Surface condition and roughness is controllable as it is largely dependent on factors such as powder morphology, build conditions and part orientation in the build volume. This can, however, sometimes be a disadvantage in cases where, for example, the desired surface finish is not aligned with the necessary direction for structural purposes.

+ Enclosed and highly controlled nature of PBF methods means that they can potentially be operated unattended enabling 24hr unsupervised processing. Some PBF vendors offer remote viewing and real-time process monitoring.

PBF Limitations

- While STl style file format is user-friendly, it limits the ability to carry design information to machines which might be useful throughout the full fabrication process.

- The inherent complexity of metal AM is also present in all PBF methods, which requiring an understanding of metallurgy as well as the technology being used, in order to apply the correct printing parameters and to ultimately achieve a print with the desired properties. Choosing appropriate user-defined parameters requires detailed knowledge and experience. While some companies provide recommended parameters, these are often for a limited number of common materials, and at extra cost.

- Nature of metal powders have many safety and health hazards associated with them that require engineering and administrative controls in oder for safe use throughout handling, storage, and processing. This results amongst other things in more costly equipment and labor.

- Precise repositioning of part within powder beds and realignment with re-coating blade limits application of PBF methods for repair operations.

- Lower fusion efficiency than DED methods

- Printing time and necessary powder volume are dependent on build volume, meaning that it is necessary to match size of product to appropriate build volume in order to avoid costs related to unnecessary capacity, materials, time, and resources.

- Metal powders are costly and PBF processes require purchasing a volume of metal powder scaled to the build volume.

- Specialty AM powders for PBF processes with qualities such as high purity, chemical cleanliness, consistent particle shapes and sizes are in limited availability and costly compared to DED

- Powder may get trapped in piece during build causing unwanted weight and material usage. This powder, however, can potentially be removed during post-processing.

- Distortion offset may only be accommodated in the x direction

Laser Beam Powder Bed Fusion

ASTM Category: PBF-L

Specific Methods: Direct metal laser sintering (DMLS)
Selective laser melting (SLM)
Selective laser sintering (SLS)
Laser Cusing

Features: Laser scanning optics utilizes magnetically driven mirrors using galvanometers quickly and accurately direct beam

PBF- L Advantages

+ Laser scanning optics utilizes magnetically driven mirrors which avoid the need to manipulate large laser head masses focusing optics (like those used in DED-L), enabling accurate and speedy prints.

+ Laser capable of penetrating 3 or more layers

+ Has been developed over time to being capable of producing near 100% density parts for some materials.

+ Support structure can function as heat sinks during build preventing movement or disorientation

+ Rapid prototype time to market

+ Can be paired with post-processing such as heat treatments

+ Recent innovation in higher efficiency diode and fiber lasers enable more efficient laser based systems narrowing the performance gap between PBF-L and the wall plug efficient PBF-EB

PBF-L Limitations

- Requires more rigid support system than PBF-EB

- Less inherently quality micro-structure than PBF-EB method. Furnace heat treatments or HIP processing may be applied during post processing to reduce thermal stresses, homogenize micro-structures or modify mechanical properties to achieve desired performance.

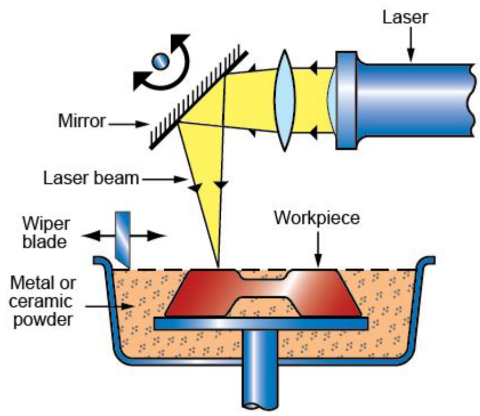
- Near 100% density only achieved for a small range of materials. Navigating flaws in bulk materials and finished components for creating predictable results has largely not yet been mastered in industry and will require effort in the coming decade.

- Technology susceptible to defects, porosity, and voids due to process disturbances or inadequate parameter selection.

- May require CNC machining in post-processing to remove support structure

- Has some geometric limitations, such as a maximum overhang angle in order to reduce need for support structure and also therefore the removal thereof.

- Is limited to a single material type within powder bed. Changing from one material to the other between prints also requires "extensive chamber cleaning to prevent contamination" which can lead to negative effects such as cracking or corrosion.



SLS Process Schematic
Source: CES

Electron Beam Powder Bed Fusion

ASTM Category PBF-L

Specific Methods: Electron Beam Melting (EBM)

Features In PBF-EB the substrate is heated before laying the powder bed, and the electron beam powder fusion process operates at an elevated temperature

PBF- EB Advantages

+ High energy density enables wall plug efficiency in many cases

+ High beam power

+ Build performed in high purity vacuum

+ When working with electrically conductive materials only, PBF-EB systems can achieve higher scan speeds by utilizing electromagnetic coils

+ Requires less rigid supports than PBF-L because powder adjacent to part is partially sintered at each layer working effectively as a support structure that is more easily removed and recycled than laser powder bed systems.

+ Heated build chamber and preheating of powders relieves stress during build process and results in products with attractive material properties, which are in some cases superior to cast metals and comparable to wrought.

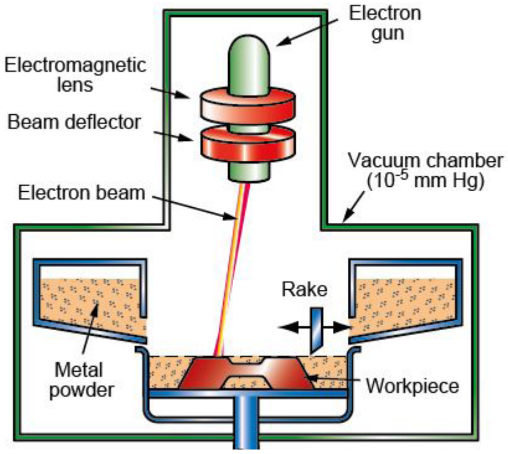
PBF-EB Limitations

- Complex and costly equipment

- Build volume takes relatively long time to cool from high preheat and processing temperatures

- Decreased part quality and accuracy when compared to PBF-L due to use of larger metal powder particle sizes than PBF-L (min 45 um vs min 10 um) required due to the electrostatic charging and repulsion of finer powders

- Fewer material options



BBM Process Schematic
Source: CES

Direct Energy Deposition (DED)

ASTM Categories:	DED-L, DED-EB, PA -DED
Specific Methods:	DED-L: laser engineered net shape (LENS); direct metal deposition (DMD); laser metal deposition (LMD) DED-EB:electron beam free-form fabrication (EBF3) Electron beam additive manufacturing (EBAM) DED-arc: Arc-Based DED (various sub-categories)
Applicable Materials:	Metals

Process

Direct Energy Deposition (DED) is a method designed to direct “powder or wire into the focal spot or molten pool created by a laser, electron beam or plasma arc directed at a part surface, completely melting and fusing the filler and translating this deposit to build up a part as directed by a 3D deposition path.”(Milewski, 2017). These processes generally stem from an industry-known process of rebuilding worn out areas under the term “build-up welding”. DED includes both powder feed processes and wire feed applications. In powder feed processes, a heat source generates a melting bath on the surface of the model onto which the metal powder is blown. In wire feed processes, a wire is fed into the melt pool produced by the arc struck between the wire and the welding surface

Ongoing Innovation

Real-time flaw detection and FEA predictive modeling of residual stress

Stainless Steel Bicycle printed using WAAM at MX3D
Image Source: Arch2o

LENS technology being used to repair a metallic part
Image Source: 3dprintingindustry.com

DED Advantages

+ Potentially enables the use of several materials in varying quantities in the same work-step

+ Well-suited to repair operations or feature additions, as it does not require a flat surface to work from and can be applied to complex surfaces. Enables re-manufacturing or re-purposing of existing parts and components.

+ Deposition rates generally faster than PBF applications

+ In some cases, the build size is not limited by the volume of the powder bed

+ Part is not submerged in powder bed during print and therefore can be monitored, and defects can be accommodated. For example, system can potentially compensate for factors such as shrinkage by "offsetting distortion and cancellation of opposing shrinkage forces and bending stresses"

+ DED methods offer stronger parametric relationship between printing process and digital model than STL files are capable of. This relationship potentially allows the CNC tool to automatically regenerate its laser path and control sequence based on changes to the digital model.

+ Uses a much smaller total volume of powder and therefore does not rely so heavily on powder reuse. This is particularly important for critical applications where virgin powder is preferred.

DED Limitations

– Relatively large geometry tolerances in comparison to powder bed methods

– Creation of complex three-dimensional geometry requires either support material or a multi-axis deposition head (Gibson et al., 2015).

– Relatively slow because movement of the entire mass of a laser head is subject to delays during hard acceleration or deceleration and requires a rigid a and massive mechanical system to maintain the accuracies and speeds required

– Software more complex than the planar slicing of STL file, also needs to account for multiple axis simultaneous motion of CNC tool path.

– Path panning increases complexity of process due to high degrees of process freedom, number of process variables and number of interactions

– Laser heads are often large and heavy limiting speed and range of movement; however, there exist options to optimize CNC system with low mass for increased speed and small size to facilitate navigating tight spaces

– Deposition rates generally less accurate than PBF applications

– Powder feed parts often require additional post-processing including CNC milling, making the process rather unsuitable for very complex applications. (AM Envelope).

– Design complexity limited in comparison to that attainable with PBF due to impracticality of support structures in DED methods

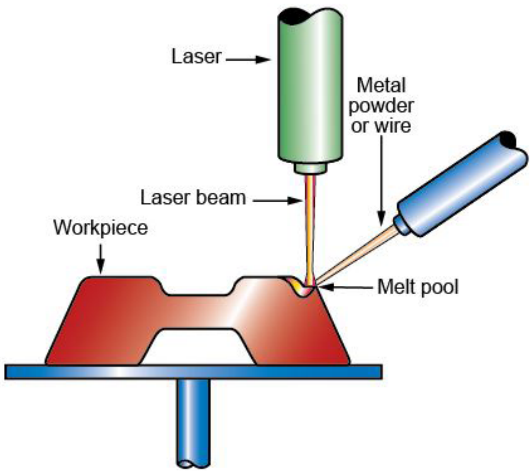
Laser Beam DED

ASTM Category DED-L

Commercial Names: LENS
Direct Metal Deposition (DMD)

Features

Fusion of metal filler into 3D shape under computerized motion control. Metal powder delivered by inert gas in inert chamber to focal point with that of laser beam, or to location of molten pool. Difference between systems typically laser head and powder delivery system.



LENS Process Schematic
Source: CES

DED-L Advantages

+ Well-suited to repair operations or feature additions, as it does not require a flat surface to work from and can be applied to complex surfaces

+ Can also be used with STL file format if it does not have significant overhangs that would require substructure

+ Can efficiently enable feed of multiple materials. Enables the possibility of creating different features with different materials in a single component print.

+ Limitations from weight and bulkiness of laser head can be offset by simultaneous motion of part relative to head.

+ Ability to turn off powder feed enables material savings, and features such as glazing surfaces, and drilling or clearing of holes or passageways

+ Part is not submerged in powder bed during print and therefore can be monitored

+ High deposition speed

+ Powder requirements less stringent than PBF and use of commercially available metal powder

DED-L Limitations

- Must be performed in highly controlled environment due to use if metal powders.

- PBF-L often preferred to DED-L due to high complexity of path planning for complex parts

- Many similar limitations to PBF-L such as dimensional accuracy, surface finish and slow build rates

- High level of residual stresses and part distortion due to larger molten pool, solidification and shrinkage stress

- High levels of engineering and administrative control for safe operation required due to environmental, safety and health considerations inherent to working with metal powders

- Requires enclosure capable of containing reflected laser light and withstanding beam movement malfunction

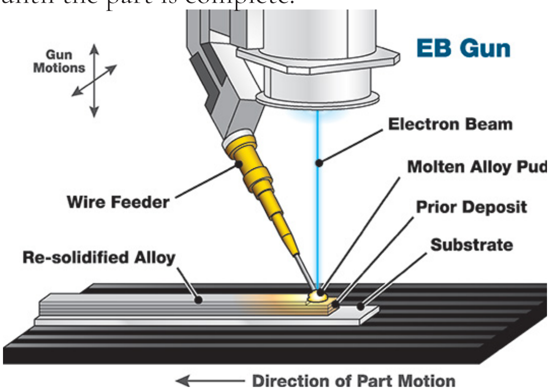
- Heat buildup can create "undesirable effects on grain growth, segregation of metallic impurities, formation of undesirable phases, defects, distortion, and other metallurgical issues"

Electron Beam DED

ASTM Category	DED-EB
Specific Methods:	Electron Beam Additive Manufacturing (EBAM) Electron Beam Free Form Fabrication (EBF3)

Features

Integrates a mobile electron beam gun, CNC motion and wire feeder withing high vacuum chamber. System fuses a deposited bead of metal, one bead at a time, one layer at a time until the part is complete.



EBAM Process Schematic
Source: Milewski (2017)

DED-EB Advantages

+ Can efficiently enable feed of multiple materials

+ High purity vacuum environment attractive for expensive or high melting point materials

+ Large chamber size less restrictive than powder beds

+ Wide range of wire alloys including titanium, aluminium, tantalum and Inconel

+ Can potentially integrate several wire feeders capable of changing from one material to another

+ Additive methods for DED often more attractive than alternative subtractive methods for costly materials such as titanium

+ Is valid solution for metal AM in space since can use existing vacuum of space environment, and wire feed is easier to control than powders

+ More energy efficient than laser based equivalent

DED-EB Limitations

- Most expensive metal 3d printers available

- Limited to relatively simple shapes

- Components have distinctly stepped weld bead overlay shape that requires machining for smooth final shape.

- Material selection limited by commercially available wire sources

- Slow cooling rate can potentially cause large grain structure and negative metallurgical effects on deposit

- Potential distortion and residual stresses in large structures likely need port process heat treatment

- Large melt pools are difficult to control and can limit application to flat position, and create poor resolution for small structural features

- Large continuous spools of material are required for large parts which require complex large wire feed mechanisms

- Massive base plates and base features are required to control effects of shrinkage and distortion

Arc based DED

ASTM Categories	Includes amongst others: GMA-DED, PA-DED
Commercial Names:	Shaped Metal Deposition (SMD) Wire+ArcAdditiveManufacturing(WAAM)

Features

Arc based DED follows similar working principles to DED-L, however with a different raw material form and energy input. Arc-based DED methods feed a wire into the melt pool that is "produced by the arc struck between the feed wire and the substrate/existing surface" (Li et al., 2017). This process is described as essentially a CNC automated version of Metal Inert Gas welding.

DED-arc Advantages

+ Best fusion efficiency of all metal AM methods available

+ Can produce large near net-shape parts at fraction of cost of PBF methods

+ Can achieve high deposition rates comparable to DED-EB, best suited to materials that don't require high purity vacuum environment

+ Cost-effective motion systems as required for arc-welding reasonable for production level applications

+ Is effective for near-net shape that can serve as blanks for forging rather than molding or casting operations.

+ Wire feedstock less complex than PBF

DED-arc Limitations

- Inferior precision, accuracy or surface quality to PBF

- Process can generate weld spatter and fumes

- Process creates lower penetrating more highly profiled rounded weld bead

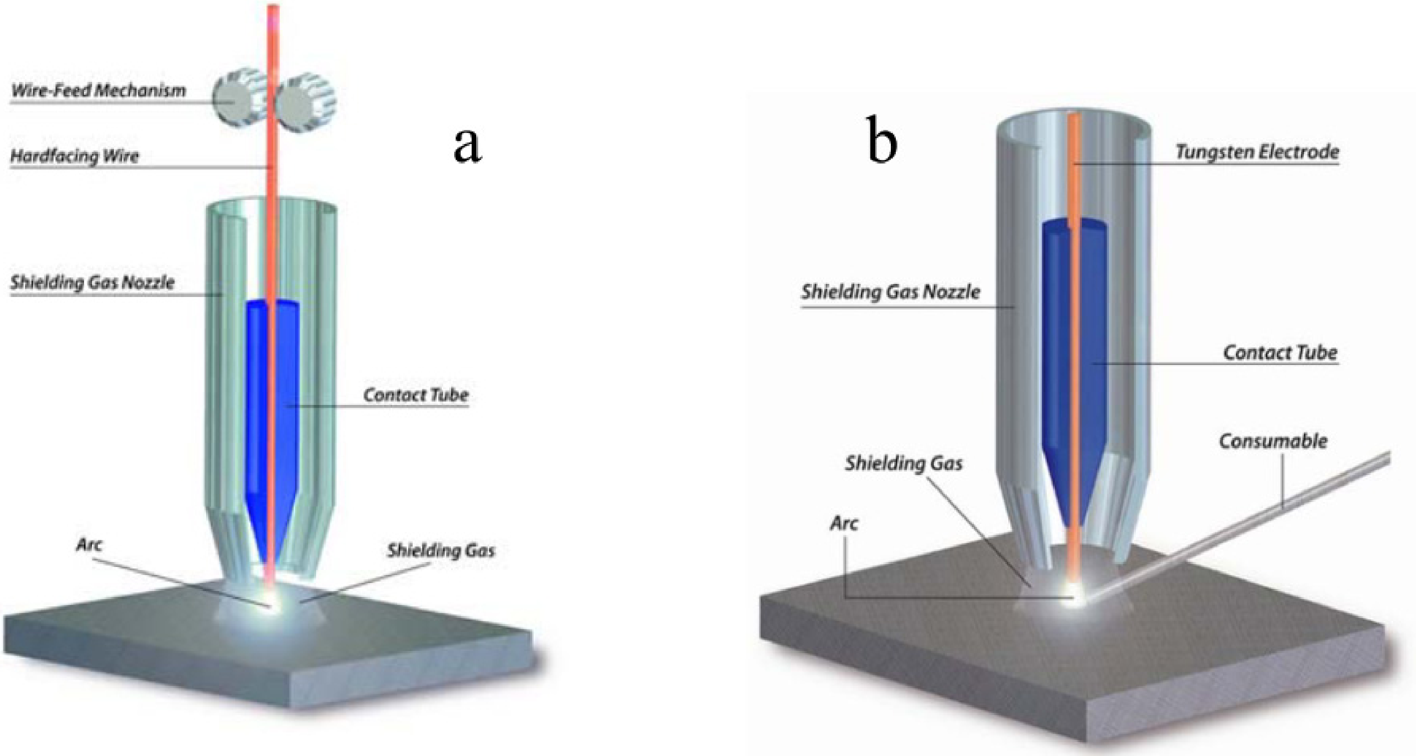
- Process creates distortion due to high residual stresses

- Heat buildup problematic in small pieces and features

- No protection from oxidation and atmospheric contamination

- Part Removal from build plate may require sawing, milling or machine tooling if it is not integral to printed part

- Additional machining required n most cases for quality finish



WAAM based processes (1a. Gas Metal Arc Welding, 1b. Gas Tungsten Arc Welding
Source: Xu et al., 2016

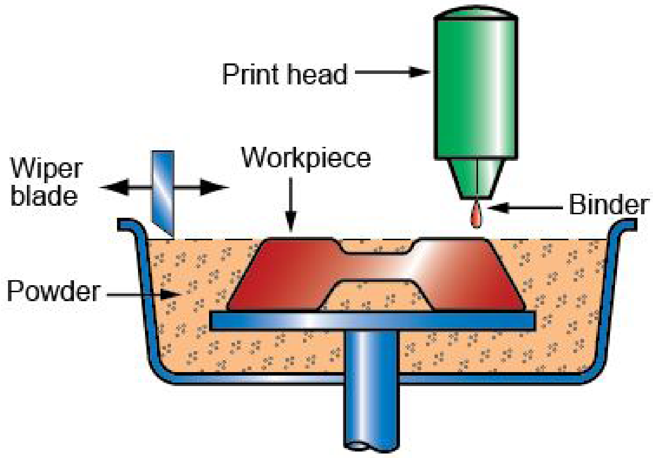
Print and Sinter AM Processes

ASTM Category	N/A
Commercial Names:	Bound Metal Deposition (BMD) by Desktop Metal and Atomic Diffusion Additive Manufacturing (ADAM) by Markforged

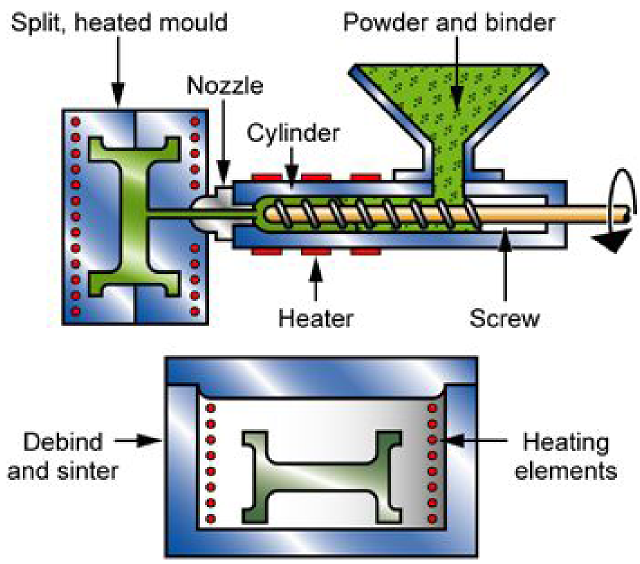
Description

BMD and ADAM are new technology that are based on many of the same manufacturing principles as binder printing and metal injection moulding. The process consists of a three step approach: printing, de-binding, and sintering. One of the major focuses in the development of this printing method is the intelligence built into the various steps based on the mode input (Waterman, 2017).

While both proprietary processes are different, each is based on three main steps: a 3d printer, a washing station, and a two step sintering process. A volume is printed using a material that combines both the metal powder and a binding agent as well as an anti-sintering agent to separate individual volumes. The parts then undergo a process to partially remove the plastic binder that encapsulates the powdered metal, and then the part is ready for the two-part sintering process.



Binder Jetting Process Schematic
Source:CES



Metal Injecton Molding Process Schematic
Source: CES

Advantages

+ Combines several steps including heat treatment into single intelligent, user-friendly production line

+ Represents many of the same advantages of metal injection moulding including a wide variety of materials, low-cost MIM powder, higher strength than casting alternatives, (die casting in particular), Higher tolerances than sand casted parts, and nearly dense parts.

+ Addresses many of the limitations of metal injections moulding such as high investment

+ cost barrier for low volume production and the limitation of uniform wall thickness

+ Built-in profiles ensure uniform heating and cooling without the residual stresses of laser-based systems.

+ Support structure is created by build material and a thin layer of de-binder that enables manual separation of elements without need for machining.

+ Structural behavior theoretically comparable to that of parts produced by metal injection moulding but not tested.

+ Can be used with available range of materials available for metal injection moulding.

+ Offers and office friendly and more production based option.

+ Production based system, according to desktop metals, is equipped with several furnaces, whose processing time is longer than the printing action. The combination of single pass jetting and the multiple furnaces are developed for mass 3d printing production and is capable of printing around 40x the volume that laser based methods are capable of producing.

+ The process uses intelligent software to regulate complex variables such as thermal profiles for metal sintering, essentially automating the applied knowledge of a metallurgist

+ Enables the custom prioritization of factors such as printing time, material usage, minimizing support material and surface quality

+ Cost effective solution compared to other AM methods

+ Single Pass Jetting (SPJ) builds metal parts in a matter of minutes instead of hours.

+ Parts are surrounded by loose powder, enabling the full use of the build envelope, part nesting, and higher productivity per build

Limitations

- Very new technology therefore not widely tested or understood. Since it is so new, most information available is published by the developers of the technology, and therefore does not offer critical insight on its shortcomings or limitations

- Excess material needs to be recycled and reprocessed in order to re-use

- Support structure necessary and must be capable of being removed manually. This could prove to be limiting geometrically for, for example, undercut geometry.

3.5
RM Precedents

The following section will take a look at a number of products that were redesigned or enhanced with the use of additive manufacturing. The first section pertains specifically to additive manufacturing in curtain wall applications, and the second will look at other industries. It is a worthwhile effort to look into other industries to see how additive manufacturing has been used to reinvent traditional products and processes. While additive manufacturing is a relatively new technology, already many industries, including architecture, medicine, automotive, and aerospace industries, have embraced the potential of additive manufacturing and improved upon standard and specialized products. This section looks at a number of case examples to understand how these improvements took form.

Rapid Manufacturing in Facades

The previous section consisted of a small inventory of methods available for the rapid manufacturing of metals. In order to establish which methods are appropriate for application for steel curtain walls, AM Envelope by Holger Strauß is referenced. This study looks at AM methods and their applicability to facade applications. The research looks at both PBF , DED, and other methods of metal AM, and creates a series of matrices that rank the methods in terms of the following characteristics: suitability for integration or parts; ability fit into conventional facades; material compatibility with facade materials; potential for customization; potential for feasibility in industry; potential for use of free form; and potential for enhancement of facade technology

The top 5 results in the matrix are as follows: SLM, DMLS, LaserCusing, Polyjet, and SLS. Only three of these are applicable to metal: DMLS, LaserCusing, and Selective Laser Melting, each of which belong to the laser based powder bed fusion family. Other AM methods, while competitive in many of the outlined criteria fall short most evidently in categories related to geometrical freedom and compatibility with existing industry. It should be noted that this matrix does not include bound metal deposition as this technology was not yet existing at the time of this publication. The author then further compares the above 5 options in terms of the following criteria: Evolution in building chamber size; evolution in new materials; potential for system integration; change of shape/form; change of engineering; authors recommendation for application. Further research and understanding of design objectives will help determine which method is most appropriate for this specific application

Quantifier	Intention
-	negative
+	positive
o	neutral

Explanation for the used quantification from AM Envelope

AM Process	Application for façade manufacturing			Potential for				Potential for AM Envelopes		
	suitable for integrated parts	fits into conventional façade manufacturing	materials suitable for façades	customisation	feasibility	use of free form	enhancement of façade technology	Summary	Ranking	processes for AM Envelopes
DMLS	+	+ +	+	+	+ +	+ + +	+	11	2	DMLS (Metals)
LENS	o	o	+	o	+	+	+	4		
EBM	o	o	+	o	-	+	-	2		
LaserCusing	+	+ +	+	+	+	+ + +	+	10	2	LaserCusing (Metals)
SLM	+	+ +	+	+	+ +	+ + +	+	11	1	SLM (Metals)
DMD	-	+	+	o	+	+	+	5		
EBF³	-	o	+	o	+	+	+	4		
CLAD	-	+	+	o	+	+	+	5		
M3D	o	-	-	o	-	+	-	1		
SLS	+	+	o	+	+	+ + +	+	8	3	SLS (with PEEK, specialized materials)
PolyJet	+ +	o	+	+ +	o	+ +	o	7	3	PolyJet (Material issues)
MultiJet	+	-	-	+	o	+ +	o	4		
Voxeljet	o	o	o	+	o	+ + +	o	4		
SLA	o	- -	-	+	o	+	o	2		
DLP	+	- - -	-	+	o	+	o	3		
3DP	o	- - -	-	+	o	+ + +	o	4		
FDM	+	o	o	+	o	o	o	2		
D-Shape	-	- - -	o	-	-	- - -	-	3		
CC	-	- - -	+	-	-	-	+	2		

Figure 3.5.1: Potential of AM processes regarding different aspects of AM manufacturing
Source: Strauß (2013)

AM processes from Matrix I	evolution in		façade systems	Architectural design		Recom-mendation	Ranking Matrix II		AM processes for AM Envelope
	size of building chamber	new materials	potential for system integration	Change of shape / form	change of engineering	Application makes sense!	Summary	Ranking	
DMLS	+	+	+	+	+ +	+	11	3	DMLS
LaserCusing	+ +	+	+ + +	+	+ +	+ +	14	2	LaserCusing
SLM	+ + +	+	+ + +	+	+ +	+ +	16	1	SLM
SLS	+	o	o	+	+ +	o	6		
PolyJet	-	+ + +	-	+ + +	+ + +	-	9		

Figure 3.5.2: Further assessment of AM potential on background of Matrix 1
Source: Strauß (2013)

ARUP Tensegrity Node

Industry

Architecture

3d printing technology

Direct Metal Laser Sintering

Designers

Galjaard, Salomé
Hofman, Sander
Perry, Neil
Ren, Shibo

Material

1.4404 stainless steel

Predecessor

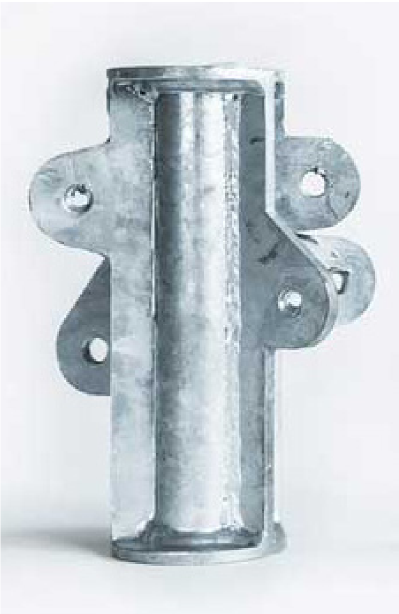
Machined steel plates, welded on a central tube (below)

Description

This design is an exploration of the use of AM technology in replacing traditional structural joints in a tensegrity structure. The design replaces an existing node made up of a reinforced steel tube with welded CNC plates for attachments, and through a series of optimization processes, generated an optimized volume that is 3D Printed in stainless steel. This project was taken on by a team from Arup with backgrounds in both building design and materials.

The node was created using direct metal laser sintering because of the capacity of the technology to create thin walls, deep cavities, hidden channels and its compatibility with the objective to optimize weight. The overall goal of the node was not only to create a node that was structurally optimized, but also took advantage of AM to "integrate as much functionality as possible" (Galjaard, Hofman, Perry, & Ren, 2015), meaning simplifying connections, and adding adaptable functions to the node.

The main geometry of the node is the result of topological optimization processes which reduce the weight of the structure initially by 50% and subsequently by 75% in the second iteration. While the first iteration was purely the topological optimization of the existing form, the second iteration focused additionally on "uniqueness, weight optimization and product-integration".



Tensegrity Node: Original Component
Source: Galjaard, Hofman, Perry & Ren (2015)

Reference:

Galjaard, S., Hofman, S., Perry, N., & Ren, S. (2015). Optimizing Structural Building Elements in Metal by using Additive Manufacturing. International Association for Shell and Spatial Structures, (August).

Tensegrity Node: Optimized Components - first (left) and second (right) iterations
Source: Galjaard, Hofman, Perry & Ren (2015)

NEMATOX II

Industry

Curtain Wall Architecture

3d printing technology

Concept Laser LaserCusing

Designer

Strauß, Holger

Manufacturer

FKM Sintertechnik GmbH

Material

Aluminium

Predecessor

Custom Aluminium Profile Connection

Description

The Nematox Node is a product developed by Strauß as a part of his doctoral research exploring the potential of additive manufacturing in facades. The Nematox is an alternative solution to post and beam aluminium curtain wall systems aimed at mitigating water leakage in free-form angled curtain walls of this kind, and thus eliminating or mitigating the need for the wet seals.

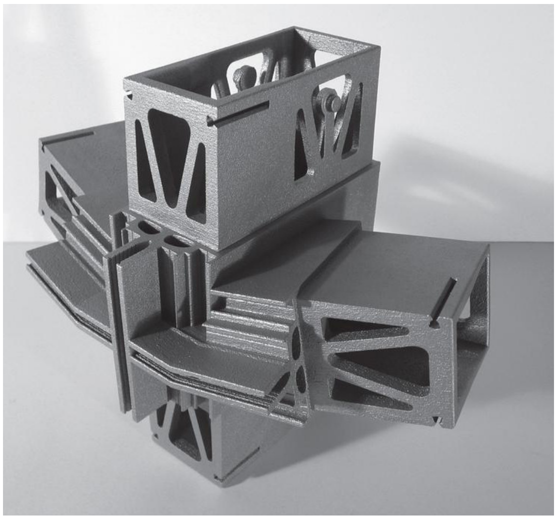
The product addresses only the critical point of the assembly, which is the node. The node, once printed becomes past of a hybrid solution that uses AM technology to improve performance of traditionally mass manufactured components. The node is a digital merging of post and beam post profiles that only requires rectangular saw cuts for assembly, reducing the risk of inaccuracies during cutting on a construction site. This particular design maintains the use of all traditional accessory parts even for complex angles.

The author tallies the hours of work involved in the printing of the two versions of the node once they are designed, Nematox I and Nematox II:
120 hrs CAD engineering for generating print-proof .stl file, and another about 15 hours of finalizing file and print preparation, 76.5 hours of printing at a 1:1 scale, and four hours of post-processing.

The result is a functional node mock-up that creates an "assembly friendly", water tight custom curtain wall joint. The design, according to Straußs report, accomplishes the following objectives:

- ► Reduction of scraps by avoiding long miter cuts
- ► Reduction of on-site cutting accuracies with 90 degree cuts
- ► Accuracy of joints is improve and thus need for later elastic sealing materials is reduced
- ► Reduces overall number of work-steps in system installation simplifying assembly
- ► Introduces high degree of prefabrication in what was previously largely on-site fabrication, reducing on-site production risks
- ► Regionally manufactured components reduces otherwise necessary transportation costs and environmental effects.

Further development for this facade could include, according to the author, the integration of fully integrated articulating parts, further engineering and material optimization.



Nematox Node
Source: Strauß (2013)

3F3D Node

Industry

Curtain Wall Architecture

3d printing technology

Direct Laser Melting

Designer

Prayudhi, Bayu

Manufacturer

Star Prototype (CHN)

Material

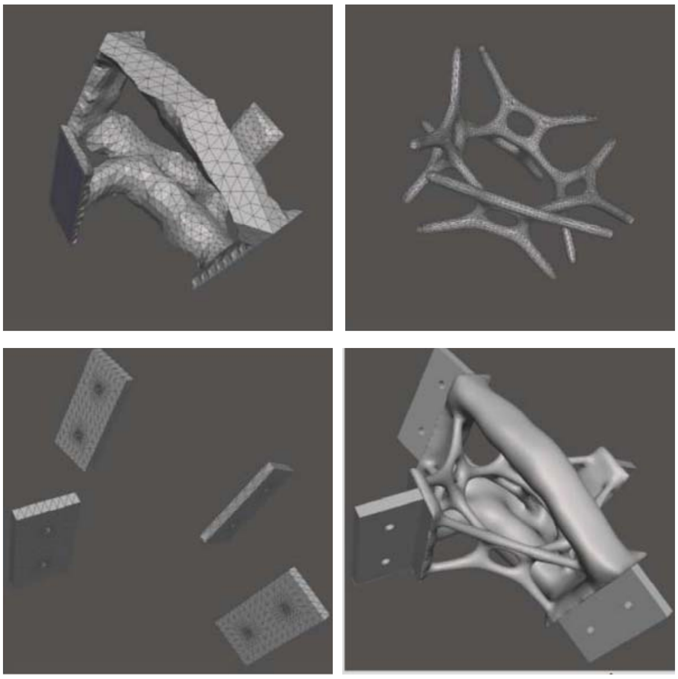
Stainless Steel

Predecessor

Welded End-Face Free-form Facade Node

Description

The 3F3D (Form Follows Force with 3D Printing) is a structural system for a free-form envelope that makes use of additive manufacturing technology and topology optimization technology to optimize the structural performance and reduce the amount of structural material necessary to accomplish a certain geometry compared to traditional manufacturing methods (Prayudhi, 2016). The prototype is developed to a quadrangular shell grid, that is first optimized using a digital form-finding process. The testing prototype is a structure that consists of stainless steel nodes that connect steel beam elements, connected by a bolted splice connection. The nodes are printed using FDM technology. The node is designed as the product of two optimization processes: "the standardized optimization process and the definite optimization process specific to its architectural function" meaning that the final geometry is the result of both the specific loads and geometry of the structure, as well as broader behavior that can potentially be expected from this kind of structure.



3F3D Node Components
Source: Prayudhi (2016)

3F3D Node
Source: Prayudhi (2016)

Corner Cleats

Industry

Curtain Wall Architecture

3d printing technology

FDM

Manufacturer

FKM Sintertechnik GmbH

Material

Aluminium

Predecessor

Large stockpiles of various sizes and types of corner cleats, and manually adjustable corner cleats



Corner cleats storage
Source: Strauß (2013)

Description

In this case, the application of Additive manufacturing was considered with the specific purpose of solving issues related to custom corner cleats in industry. Currently, in order to fulfill the demand for readily available corner cleats to adhere to various systems, various sizes, and various geometries, two solutions are available the first, to mass manufacture and store the entire range of necessary options, which results in an unnecessary amount of capital invested in manufacturing kilometers of profiles to stock in inventory regardless of the actual demand; and second, the use of manually adjustable hinged corner cleats which reduce the structural efficiency of this inherently structural component. Here AM is mostly advantageous in terms of effective low-quantity manufacturing, more than it presents advantages in terms of digital design. Rather, this application proposes a solution in which windows angles are digitized, applied to CAD files for production, and printed on an as-needed basis. A few additional features were integrated such as digital material reduction, use of a lighter material, and snap on features.

Original al. corner cleat and first prototype w/integrated snap-on functions and lightweight structures (right)
Source: Strauß (2013)

Optimized T Connector

Industry

Curtain Wall Architecture

3d printing technology

DMLS

Manufacturer

FKM Sintertechnik GmbH

Material

Stainless steel

Predecessor

Standard T-connector for a stick-built aluminium curtain wall system

Description

The T-connector is an optimized component that makes use of digital design, topological optimization and additive manufacturing to produce cost-effective custom components that enable free-form geometry and improve the structural efficiency of traditional T-connectors. The product, according to the author, includes the "benefits of prompt production, but also the performance characteristics within the facade system". The connectors, which have the purpose of transferring loads from beams into pillars, are meant to ensure a "force-fitted connection of the components", that improve on the less-than-ideal structural performance and geometrical freedom of the current component used for non-orthogonal facades. In this component, all necessary angles and boring are digitally integrated improving the fit of the connections as well. One of the most considerable improvements of this system is the material savings achieved through topological optimization, which reduced material use by 25%. this system, similar to the Nematox node, is meant to be implemented as a hybrid solution, and is entirely adherent to the existing curtain wall infrastructure. This product has the ambition to become a standard process solution that can evolve directly from digital planning to CAD-CAM production.

From left to right: Traditional T-Connector, polymer printed first design iteration, final design
Source: Strauß (2013)

Optimized T Connector
Source: Strauß (2013)

3dXM Canal Bridge

Industry

Architecture/Bridge Design

3d printing technology

WAAM

Manufacturer

3dXM

Material

Stainless steel

Predecessor

Traditional Canal Bridge

Description

Coupled typical industrial robots with 3D printing technology. Multidisciplinary team of deign, structural engineering, metallurgical experts, digital production tools experts, construction experts, computational hardware experts, robotics specialist, welding specialists, and a safety team. Project design began with pure application of topological optimization with purpose of reducing material use, however in development, initial design proved too complex for anticipating structural behavior of the 3d printed product. The second iteration, centered around a sheet-construction approach that, worked primarily with compression forces using stress analysis software to generate force lines. (Estes, 2018). In this case, as will be the case in a facade application, the structural requirements have a significant in impact on the printing method selected, since this type of behavior is integral to the product.

MX3D Bridge
Image Source: MX3D.com

GE Leap Engine

Industry

Aviation

3d printing technology

Direct Metal Laser Melting

Manufacturer

GE Additive (prev. Concept Laser and Arcam)

Material

cobalt-chromium alloy

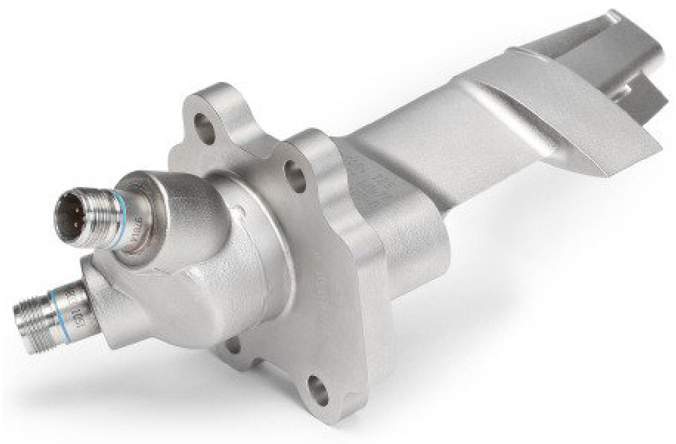
Predecessor

CFM56 = 2,200 kg

Description

Half of the engine is printed, reducing 900 separate components to 16. Printed parts 40% lighter and 60% cheaper that traditionally manufactured ones. The engine nozzle, an extremely challenging product to produce within traditional manufacturing means, was consolidated from 20 parts into a single unit, weighing less than 25% of the original parts' weight. 3D printed nozzle design reduces fuel consumption by approximately 15% and reduces engine emissions. 5x durability increase, no need for frequent part replacement, Certified for use by U.S. Federal Aviation Administration (GE).

The components in this case went under rigorous engineering and optimization to maximize the efficiency of the design. Just this product went through several years of development. In this case, AM is not taken advantage of for the concept of mass-customization, as they will be mass-manufacturing thousands of the same component. Rather, AM is necessary only for the performative improvements that the reduced manufacturing constraints enable, and because AM enables the use of a different, lighter material that is typically difficult to cast.



GE Leap Engine Nozzle
Image Source: GE

Motorbike Swing Arm

Industry

Automotive

3d printing technology

FDM printed sand moulds

Manufacturer

Lightning Motorcycle

Material

Polycarbonate

Predecessor

Heavy piece of milled aluminum pipe

Description

Key component of fastest production bike on the planet. Made of 3d printed polycarbonate core is subsequently wrapped in carbon fiber. Design starts with weight and strength as requirements as base design elements, rather than a predetermined shape of metal. Lattice structure saves weight and material wastage. Next iteration will combine 3d printing composites technologies. Polycarbonate 3d printing environment requires a high-temperature hot end and heated print bed, an enclosed build chamber, and effective bed adhesion (Tilley, 2014) (Rhodes, 2015)

Motorbike Swing Arm
Image Source: Tilley (2014)

Dental implant surgical guide

Industry

Medicine/Dentistry

3d printing technology

Polyjet by Objet OrthoDesk

Manufacturer

Individual Dentistry Offices

Material

Biocompatible MED610 or MED620

Predecessor

Manual surgery, gypsum models or laboratory-fabricated dentures

Description

Greater design freedom than traditional methods that have limited options for specific diameters, positioning and support. Implant does not require damaging healthy teeth. Coupled with computer-aided-design/computer-aided-manufacturing (CAD/CAM) cone beam computed tomography – also called (CBCT) scanning technology for producing a surgical template. Average cost savings of 50 percent to 85 percent from previously outsourced surgical guide options, and reduced what was previously two to three week turnaround time to 48 hours.

The advantage is similar to a previous example, in which the custom AM pieces replace a large library of components typically used to satisfy the demand for variation. It is notable that this process makes use of AM is used in this case to facilitate a process, rather than a flan product that will be used long-term. It also utilizes 3D scanning to create the digital platform (an stl file) from which the guide is produced. It is also worth noting that prior to polyjet printing, another method of AM was employed for the surgical guides, namely SLA printing, but that the difference in resolution between the printed guide and the scan of the patients mouth was problematic.

3D printed implant surgery guide
Image Source: Stratasys

Titanium Medical Implants

Industry

Medicine

3d printing technology

Electron beam melting

Manufacturer

CEIT Biomedical Engineering

Material

Titanium alloy (Ti-6AI-4V)

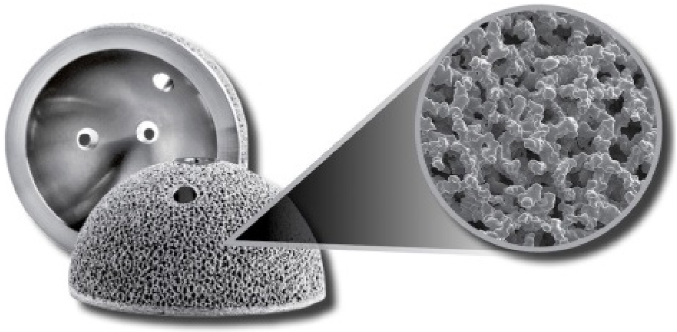
Predecessor

Traditional titanium implants with single density and lower quality of ossointegration

Description

Material to meet all the eligibility criteria for the long-term implantability as specified by ASTM F136, and possesses the required biocompatible and mechanical properties. Enables the design of implants with a porous structure that enable ossointegration. Enables the creation of implants with physical properties very similar to human bone properties (Raphel, Holodniy, Goodman & Heilshorn 2016).

Additive manufacturing in this scenario requires a precision that is likely much higher than that required for facade applications, both because of the scale and the complexity of the geometry of medical implants. The final geometry is dictated by an algorithm that simulates and the density of 3D printed material for ossointegration to take place.



Orthopedic hip replacement sockets
Image Source: Olson (2018)

Artificial Ear Implant

Industry

Medicine

3d printing technology

Integrated Tissue–Organ Printer (ITOP)

Manufacturer

Wake Forest Baptist Medical Center

Material

Cell-seeded hydro-gel matrix

Predecessor

Non surgical: headband bone conduction devices, spectacle bone conduction hearing aids. Surgical: Canalplasty, Bone Anchoring Hearing Aids, Bonebridge, Vibrant Soundbridge.

Description

ITOP system has three major units, namely the axis stage/controller, the dispensing module including multi-cartridge and pneumatic pressure controller, and a closed acrylic chamber with temperature controller and humidifier. Printer layers patterns of cell-containing gels and biodegradable, plastic-like materials followed by a temporary polymer outer shell that helps the entire structure hold up during implantation. Once implanted, the "plastic-like" support materials degrade, while the cells secrete a "supporting matrix" that helps maintain the implant's shape and negates the need for permanent supporting materials. (Jung, Lee & Cho, 2016)

This type of process involves the consideration of several live factors like keeping cells in the printing matrix alive until surgery, and the degradation of the support material. This is an extreme example of an overall process that involves several sub-processes, and requires the careful overlaying of these sub-processes over time.

3D printed implant surgery guide

The application of AM technology in the medical field also faces regulatory obstacles even more stringent than application in architecture. While this technology continues to advance, and has proven successful when installed under the skin of mice and rats, it has yet to be proven and approved as a safe application for humans.

3.6
Innovation in RM technology

The limitations for metal RM can generally be divided into two categories: physical limitations, which pertain to the fabrication of the RM part itself, limited by scientific factors and includes material limitations and technological limitations; and social limitations, which pertain to societal factors and includes legislative limitations and standardization in practice, and financial limitations. Most physical limitations, given the continued advancement of metal additive manufacturing research, will be overcome in time. There are a number of individuals and organizations taking on this research. Much of it focuses on metallurgy as well as development of both the hardware and software related to rapid manufacturing in hopes of refining existing techniques and creating new techniques that enable more reliable, better performing, and more cost-effective RM solutions. Once the major material and technological limitations are resolved, it is likely to follow that social limitations will become less burdensome: AM solutions will become standardized and accepted in industry, removing the social barrier, which will in turn increase the prevalence of AM technology and thus also likely somewhat alleviate its financial barriers. The author of Additive Manufacturing of Metals suggest that by the time the technology itself is ready to be commonly used in industry, that the technology will have become affordable to small and medium-sized businesses. (Milewski, 2017)

Keeping up with innovation

Rapid manufacturing is a rapidly and constantly evolving industry, largely thanks to its open online platforms, and its relevance across industries. Keeping up with the latest innovation surrounding this technology is a broad task. The following is a list of resources available that are good repositories of relevant innovation in the AM Manufacturing community.

► Additive Manufacturing European Forum (www.rm-platform.com) : online platform with the objective of contributing to a coherent strategy, understanding, development, dissemination and exploitation of AM

► Wohlers Report: a yearly publication published since 1996 covering various facets of 3D printing and additive manufacturing, including business, product, market, technology, research, and application. The Wohlers Report is often referred to as "the 'Bible' of the 3D printing industry" (engineering.com)

► Metal AM: quarterly magazine publication (and digital edition) of news and articles on the metal Additive Manufacturing of metals published by Inovar Communications Ltd.

► Thingiverse (www.thingiverse.com): an online largely open-source repository for hardware design.

In an article published by Forbes in 2014 on the role of software giant Autodesk in fabrication, Jordan Brandt, a technology futurist at Autodesk is quoted saying "hardware, software, and materials are all combining. It's hard to differentiate between them now. To innovate in one, you have to innovate in all three". And true to this statement, innovations in all three sectors are continuously being researched, developed and tested in different variations and combinations in order to advance additive manufacturing technology. The following is a growing collection of current research endeavors related to the rapid manufacturing of metals that are relevant to this research.

Print Quality

► Improved surface finish
► Predictable structural behavior
► Improved structural behavior
► Tighter printing tolerances
► Improved reliability of prints

Material

► Increased material safety
► Simplification of material handling
► Augmented range of commercially available materials
► Development of materials and alloys optimized for AM
► Improved hybrid/dual material printing
► Printing of biomaterials

Production

► Increased build chamber size
► Improved volume production

Process

► Increased print speeds
► Streamlined processes
► Improved CAD to CAM compatibility
► Improved CAD to CAM work-flows
► Elimination of need for post-processing
► Compatibility and with Post-processing

Process Intelligence

► Cloud-based processes
► Smart automation of printing parameters
► Reactive printing
► Automatic calibration of equipment

Accessibility

► Office friendly metal printing systems
► Safe and user friendly systems

Methods

► New RM Printing technology Methods
► Development of printing methods for increased range of materials

AM Trend Analysis

Gartner, an analytics and consulting company, has been publishing an annual study focused on the main AM trends. The study includes Gartner's "Hype Cycle", a graphic representation of the adoption and maturity of a technology, focusing on innovations in the early stages of market adoption (Gartner). The hype cycle identifies 5 steps to a trend: Innovation trigger, peak of inflated expectation, through of disillusionment, slope of enlightenment and finally the plateau of productivity. The study also projects the expected number of years to mainstream adoption. Figure 3.6.1 illustrates the general steps within each phase of a trend. While the Gartner scale for additive manufacturing (Figure 3.6.2) includes all facets of additive manufacturing, it comprises an analysis of various trends pertaining specifically to RM. Interestingly, both Direct Energy Deposition and Powder Bed Fusion technology are at the early steps of the Peak of Expectation, and projected 5 to 10 years to mainstream adoption, which is a promising projecting for the future of metal additive manufacturing in architecture.

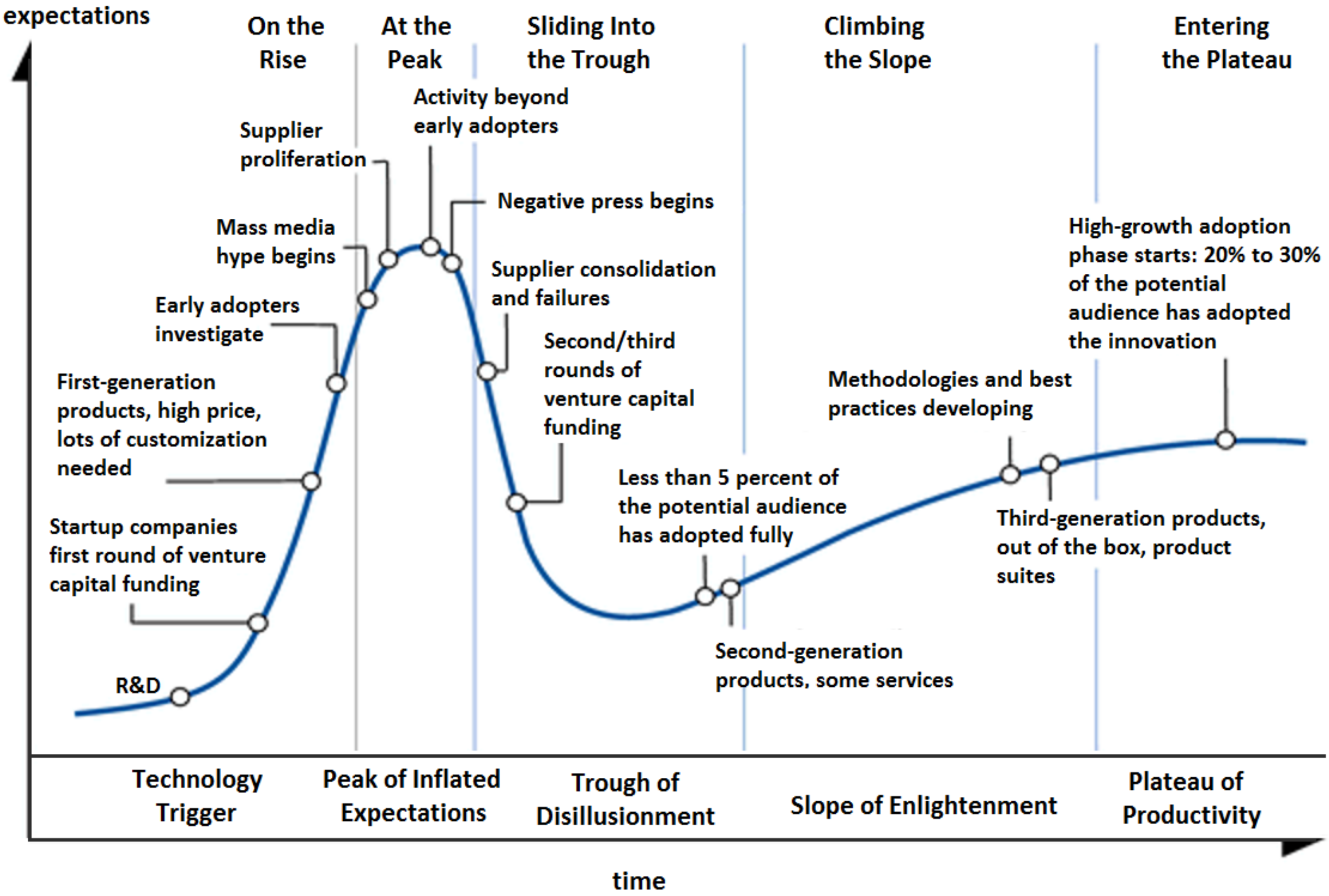


Figure 3.6.1: Gartner Trend Analysis Legend
Source: Wikipedia

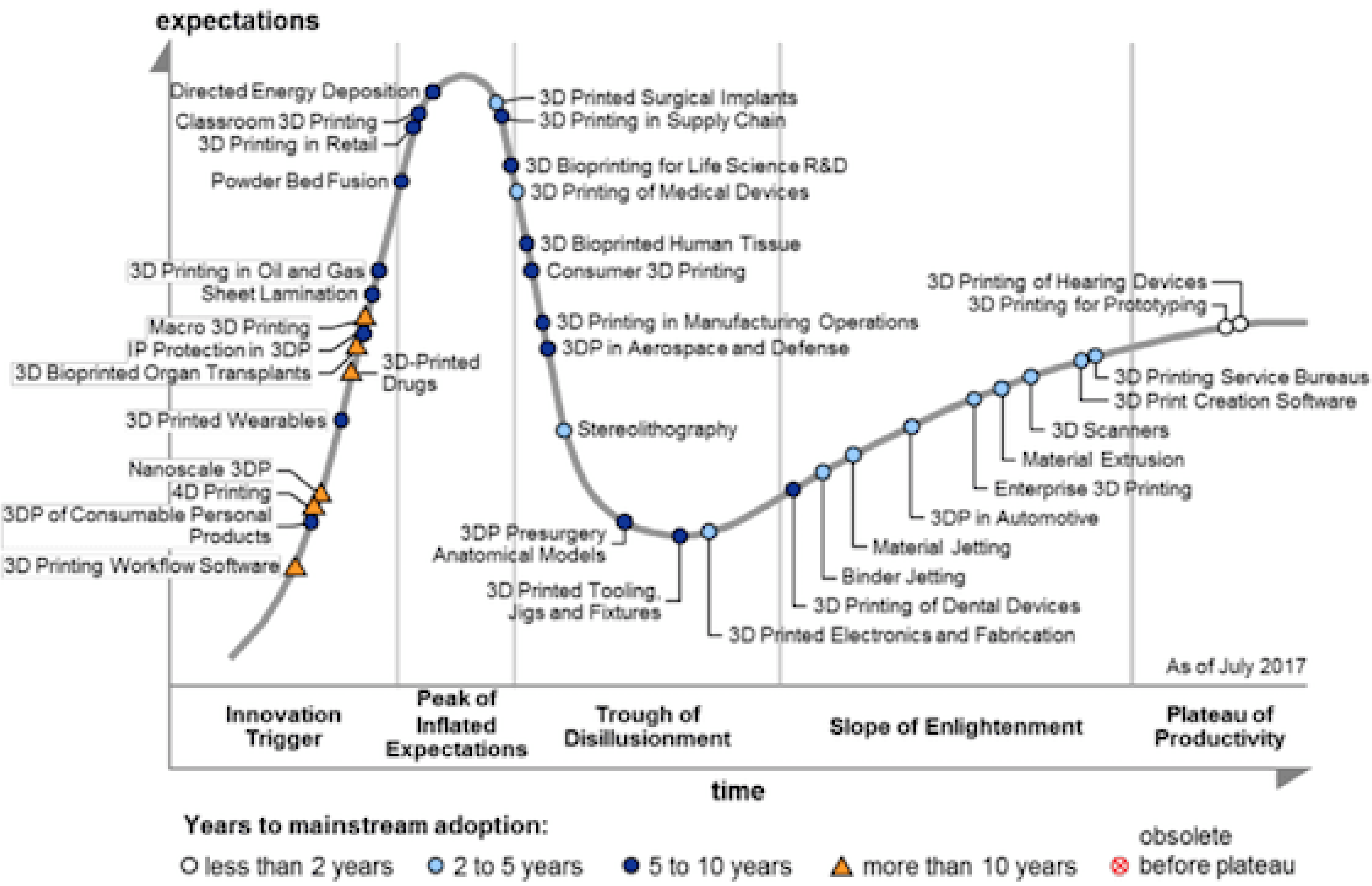


Figure 3.6.1: Gartner Trend Analysis For Additive Manufacturing Technology
Source: Wikipedia

Summary and Conclusions on Rapid Manufacturing

Rapid manufacutirng is and increasingly popular and accessible technology that is changing the possibilities of manufactuinrg, creating possibilities for economical “mass customization” and enabling the production of elements and features that heretofore were not possible or not cost-effective. Digitally Optimized Design is opening up new possibilities for intelligent design and enabling digital data, which can have many forms and sources, to directly inform a design. Structural Optimization is a relevant facet of digitally optimized design that uses digital structural analysis to optimize the structural performance of a subject.

This paper presents an overview of the relevant metal additive manufacuting methods for a primary structural elements of steel curtain walls. This include powder-based printing methods, direct energy deposition, as well as a few very recently developped metal AM methods. For the purposes of this project, laser-based powder bed fusion processes bound metal deposition and Atomic Diffusion Additive Manufacturing are suitable options worth consideration. While the first is an option that is becoming increasingly accessible, reliable, and accepted in industry, the second and third are newer technology that have the potential to overcome some of the challenges of powder based methods, particularly those related to the effect of the micro-structure of the printed product on its structural behaviour.

The study of precedents accross industries is used to develop an understanding of the potential that the introduction of additive manufacturing can have on the traditional design of a product. A small selection of features such as structural optimization, weight optimization, in place manufacturing, integrated moving parts, use od 3d scanning technology, micro-scale details, are highlighted in relevant case examples.

Rapid manufacturing is a growing trend that is picking up speed in many industries. In the rapid manufacturing of metals, powder based fusion methods and direct energy deposition methods are trends that can be expected to reach commonplace adoption in industries in the next 5 to 10 years. This timeline suggests that the present is an excellent time to investigate thoroughly and seriously the potential of additive manufacturing in architecture. While technology becomes increasingly reliable, and its behaviour increasingly predictable and understood, companies that explore the potential of additive manufacturing will be at the cutting edge of their industries when the technology reaches the “Plateau of Productivity”.

04
Nodable.

The purpose of the design task is to develop a node that is superior to the traditional alternatives by using additive manufacturing technology. Based on results of literature research and conversations with industry professional at Jansen, four categories were identified as being key focuses for design considerations: geometrical freedom, assembly efficiency, structural optimization, and printing considerations.

The design task will be divided into two phases: base design (Nodable) and advanced design (Nodable$^+$). The generic design is the definition of a geometric logic and assembly strategies that can be applied to any hypothetical free-form facade. This logic makes up the fabric of the base parametric definition that defines the overall geometry of the node, and how it connects to incoming mullions. The advanced design is an enhanced version of the node that takes further advantage of digitally optimized design and additive manufacturing to optimize the node using topological optimization. For this research, a hypothetical facade is analyzed and the data from that process is used to optimize the structural performance of a specific node.

A series of basic requirements are defined for each category. Requirements are divided into two orders of priorities: 1st order priorities and second order priorities. 1st order priorities ensure that the design must at a minimum perform the basic requirements demanded by curtain wall systems as outlined in EN 13830, as well as a number of additional specific improvements. 2nd order priorities are desired qualities that the design should, if possible, strive to achieve.

NOTE: All graphics in sections 4.0 through 4.6 have been produced by Author unless otherwise noted

Geometry Requirements

1st Order Priority

- Ability to accommodate 3 to 6 incoming mullions/ transoms at varying incoming planes and angles.
- Provide adequate surface for air/water/vapour control
- Ability to accommodate in a single node both concave and convex angles
- Compatible with typical VISS curtain wall mullion sections

2nd Order Priority

- Aesthetically pleasing
- Minimize visual intrusions/obstructions

Assembly Requirements

1st Order Priority

- Ability to connect to typical curtain wall mullions
- Only requires 90º cuts for incoming mullions
- Can Accommodate incoming mullion between two fixed points

2nd Order Priority

- Convenient assembly
- Minimize visible joints
- Minimize visible attachment hardware
- Use only dry seal

Printing Requirements

1st Order Priority

- Fit in Typical Printing bed (250x250x200)
- Provide escape path for printing powder
- Provide Adequate tolerances between shells

2nd Order Priority

- Minimize Material Use

Structural Requirements

1st Order Priority

- Provide reinforcement and system proportions based on engineering judgement

2nd Order Priority (Advanced Design)

- Optimized to enhance performance
- Optimized to minimize material use and printing volume

4.1
Solutions Matrix

The solutions matrix is an exploration of relevant design solutions based on the design framework. This matrix allowed the systematic exploration of multiple design solutions in the early stages of the project. The matrix is divided into three categories pertaining to the three major requirements categories for the design: Geometry, Structure: and Assembly. Each section of the matrix includes a description of the specific design property in question, a range of possible solutions, the advantages and disadvantages of each options, and relevant images. For each section, the selected solution(s) is flagged. Development of selected solutions are covered more in depth in later sections.

Geometry

Joint Aesthetic

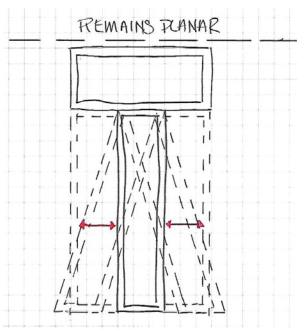
The proposed solution will be placed within an existing system. As such, it needs to respond aesthetically to its context by either conforming to or straying from it. The decision, whether it is in one direction or the other must be made deliberately.

Maintain profile aesthetic of typical joint as closely as possible, adding interior reinforcement if needed

+ Aesthetically Simple

+ Maintains functional properties of control surface and structural properties of entire profile

- Inevitable change in profile due to planar rationalization

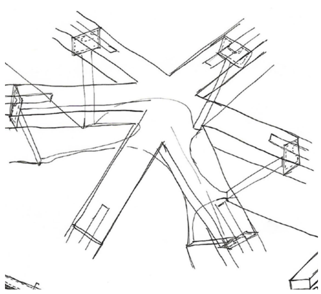


Allow Optimization to redefine part of joint aesthetic

+ Give CW systems somewhat more interesting aesthetic, while maintaining its general profile

+ Maintains functional properties of control surface

- Requires additional Engineering/ Optimization



Selected Option

Create entirely new geometry

+ Gives CW systems entirely new aesthetic/identity

- Requires new solutions for air/ water/vapour management

- Potentially requires additional engineering

- May appear inconsistent with rest of system

Image Source: Prayudhi (2016)

Planar Resolution

The intersection point of any number of incoming mullions/transoms requires the resolution of a control surface that enables the application of air/water/vapour control components. Current base system limitations only allow a maximum of two incoming planes that facet orthogonally in either pure x or y direction. Mathematically, any two planes intersect at a single line. With 3 to 6 incoming mullions each with its own free-form plane, this means that each set of adjacent planes will generate one line, and in all likelihood, none of these lines will intersect. This makes the task of having a rational surface for adding the control layers is a difficult task with simple rational geometry. The available solutions work from planes prioritizing the main control surfaces of the incoming mullions and attempts by providing a logic to adapt the incoming planes into manageable control surface(s)

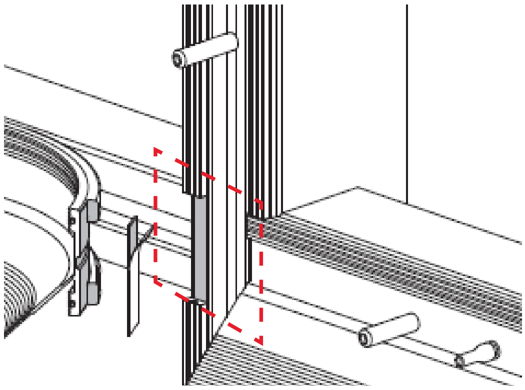


Image Source: Jansen AG, Processing and assembly

Use of single plane/double plane geometry that does not need original planar resolution

\+ Conforms to limitation of existing system

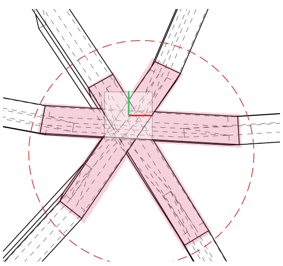
\- Does not adhere to basic requirements for geometrical freedom

Resolve geometry by cutting each incoming plane at average plane

\+ Simple geometric center means simple geometric transition to center

\- Requires faceted glass, or additional cladding element over region not planar to glazing plane

\- Creates significant changes in cross-section

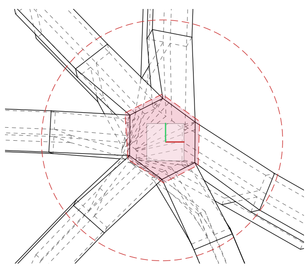


Resolve geometry by bringing all incoming planes onto singular plane by warping or faceting.

\+ Simple geometric center means simple geometric transition to center

\- Requires faceted glass, or additional cladding element over region not planar to glazing plane

\- Creates significant changes in cross-section



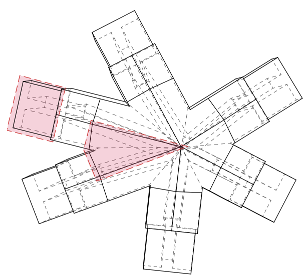
Resolve geometry by gradually morphing to point

\+ Gradual planar transition enable continuity of elements

\+ Maintains relative planarity within tolerance that enables full planar components

\- Not rational geometry requires operations such as averaging and projecting to build near-rational geometry.

\- Requires more complex modeling operations to develop geometry



Selected Option

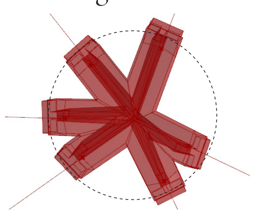
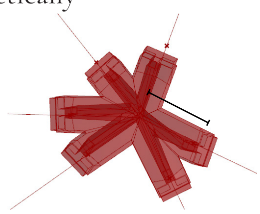
Printing Scope

Components within assembly to be 3D printed under design solution.

Print joint structure to resolve control surface and main geometry + Minimal printing - Design and geometrical solution needs to be entirely compatible with existing system components **Selected Option**	Print other Steel members such as glazing supports, pressure plate, cover profiles. + Simplifies assembly and increases level of prefabrication + Consistent aesthetically + Similar geometrical solution applied to components across section - Requires additional printing (costly) - Requires additional design **Selected Option**	Print other non-steel components, namely gaskets + Similar geometrical solution can be applied to other node components creating consistent assembly across section - Additional printing - Different printing process(material) - Exact material may not yet be commercially available for 3d printing **Selected Option**	Print/Develop supporting tools such as cutters and templates + Potentially maximizes use of mass-produced products - Increases printing - Would likely require printing individual tool for each unique angle, adding level of complexity in fabricating assembly

Printing Reach

Extent of node arms from center to connection with incoming mullions

Equal distance from center + Joints equidistant from intersection point - Requires larger printed node - May be limited by printing bed size - Need to accommodate larger moment forces 	Minimum possible distance from center + Less Printing required (maximizes use of mass-manufactured components) + Minimizes moment forces at joint - Joints not equidistant from intersection point may be displeasing aesthetically  **Selected Option**

Attachment					
Attachment Mechanism					
The node requires a means of attaching the incoming mullions to the node. As the geometry is free-form, it will be common that a member will have to be installed between two fixed points. In addition to this, it is desirable that the node have both an option for a moment connection and a pinned connection for design freedom. As such, the range below presents a range of options that are both for 1 and 2 fixed point installation, and for pinned or moment connections.					
1 Fixed Point	**1 or 2 Fixed Points**				
Fixed protruding spigots	Slip in Connection + Simple assembly - Creates large visible Joints	Screwed/Bolted Connection + Simple assembly - Potentially Visible hardware (particularly if needs to be moment Connected) - Difficult access to resolve if connection to be hidden - Would likely require additional prefabrication to incoming mullions	Drop/Rotate In + Simple assembly - Would likely require additional prefabrication to incoming mullions (attachment male/ female)	Welded Connection + Simple Design + Superior Structural Performance + Moment Connection - Labor intensive assembly *Selected Option*	Integrated Deployable Spigots + Simple Assembly - Requires ability to print integrated Parts - Tight printing tolerances for Integrated Parts *Selected Option*

4.2
Digital Workflow

As noted in the AM section of the report, the nature of additive manufacturing is rooted in digitally optimized design. This project takes a design from Computer-Aided Design (CAD), through Computer-Aided Engineering (CAE) and finally to Computer-Aided Manufacturing (CAM). The use of digital tools is integral to the development of the design. The process will require the transferring of data between digital platforms. While there are many powerful digital tools available for designers and engineers, oftentimes these digital tools are incompatible. Software incompatibilities can cause inefficiencies and bottlenecks in product development that increases the man-hours necessary to complete a product and ultimately negatively affect its overall value. A good digital workflow is key in ensuring that the process that takes advantage of all of the possibilities of digital design and additive manufacturing, does not create inefficiencies during the design phase by bouncing between or across incompatible digital platforms.

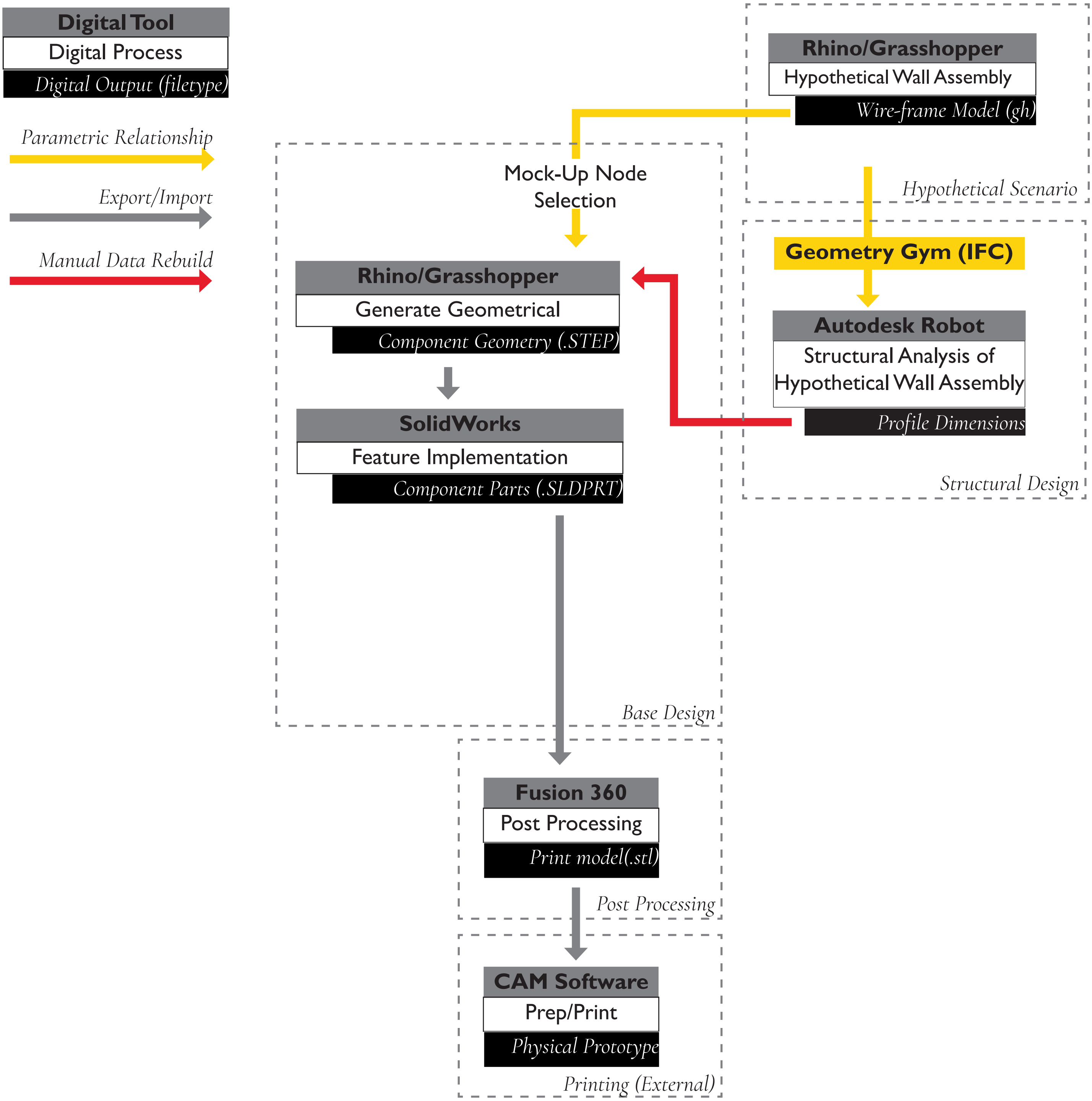
The digital workflow for this project uses Rhino/Grasshopper as the main platform for geometrical development. It is selected for its parametric abilities, dual NURBS and mesh element modeling capabilities and user friendly interface. The parametric nature of the software renders it an effective tool for developing a definition for a project such as this one, which has a number of variable input parameters (Figure 4.2.2). Other analysis tools such as Autodesk Robot and Optistruct are used for specific analysis used to further the geometric development of the node. Geometry Gym, a tool developed to facilitate project data exchange by "using a combination of OpenBIM formats (primarily IFC)" (Mirtschin), as well as Excel, are used to communicate data between applications in such a way that allows for either unidirectional or bi-directional communication as necessary.

Analysis Tool Selection

The selection of which tools will be used throughout the digital workflow if of great importance. Tools must perform a prescribed functionality, and be able to effectively communicate and translate its results to other platforms in order to enable an effective workflow. In addition to this, the workflow must be compatible with the team that is undertaking the effort. This means that the appropriateness of a tool goes beyond the ts functionality, but also needs to fit within the capabilities of the team. Does everyone have access to the tool? Does everyone know how to use it? Does it have a steep learning curve? Such questions were compiled into a chart that compares a handful of structural analysis and topological optimization tools that were evaluated for use in this application. For final selection, a hierarchy of preference is established for consecutive applicasions, prioritizing a **parametric relationship** with the main platform, followed by export/import capabilities using tools from **software suites**, followed by export/import capabilities based only on **filtype compatibility**, and finally - the least desirable path - **manurally rebuilding data**.

As Rhino/Grasshopper is the main platform used for the development of the product, compatibility with the software, either directly or through a third party platform is very important. In addition to this, analysis for the project require beam structural analysis for member sizing and eventually forces at beam ends. This effort was undertaken with support from the team at Jansen.

With the main analysis tools selected based on the aforementioned factors, a digital workflow is devised with the addition of intermediary platforms where necessary. This workflow for this project illustrated in Fugure 4.2.1 denotes the different steps in the overall process, the different digital tools that are utilized, the different inputs and outputs for each step of the workflow, the potential directions for effective information exchange, and the different types of relationship between steps in the overall process.



Digital Tool
Digital Process
Digital Output (filetype)
Parametric Relationship
Export/Import
Manual Data Rebuild
Rhino/Grasshopper
Hypothetical Wall Assembly
Wire-frame Model (gh)
Hypothetical Scenario
Mock-Up Node Selection
Geometry Gym (IFC)
Autodesk Robot
Structural Analysis of Hypothetical Wall Assembly
Profile Dimensions
Structural Design
Rhino/Grasshopper
Generate Geometrical
Component Geometry (.STEP)
SolidWorks
Feature Implementation
Component Parts (.SLDPRT)
Base Design
Fusion 360
Post Processing
Print model(.stl)
Post Processing
CAM Software
Prep/Print
Physical Prototype
Printing (External)

Design Phase: List of Input Parameters

Geometry Input Parameters

Free-form facade wire-frame

Profile Curve: Pressure Cap End

Profile Curve: Cover Cap Side Section

Profile Curve: Gasket Profile (Straight)

Profile Curve: Gasket Profile (Angled)

Dimensional Input Parameters

Section Depth:	95 mm
Face Width:	50 mm
Flange Section Width:	15 mm
Face Depth:	30 mm
Section Profile Thickness:	2.5 mm
Glass Thickness	35 mm
Cover Cap Height	16 mm
Exterior Gasket Thickness	10 mm
Interior Gasket Thickness	10 mm
Printing Tolerance:	0.2 mm
Transition Zone Length:	40 mm
Connecting Spigot Diameter:	10 mm

Structural Input Parameters:

End Conditions
Support Conditions
Load Conditions
Material Properties

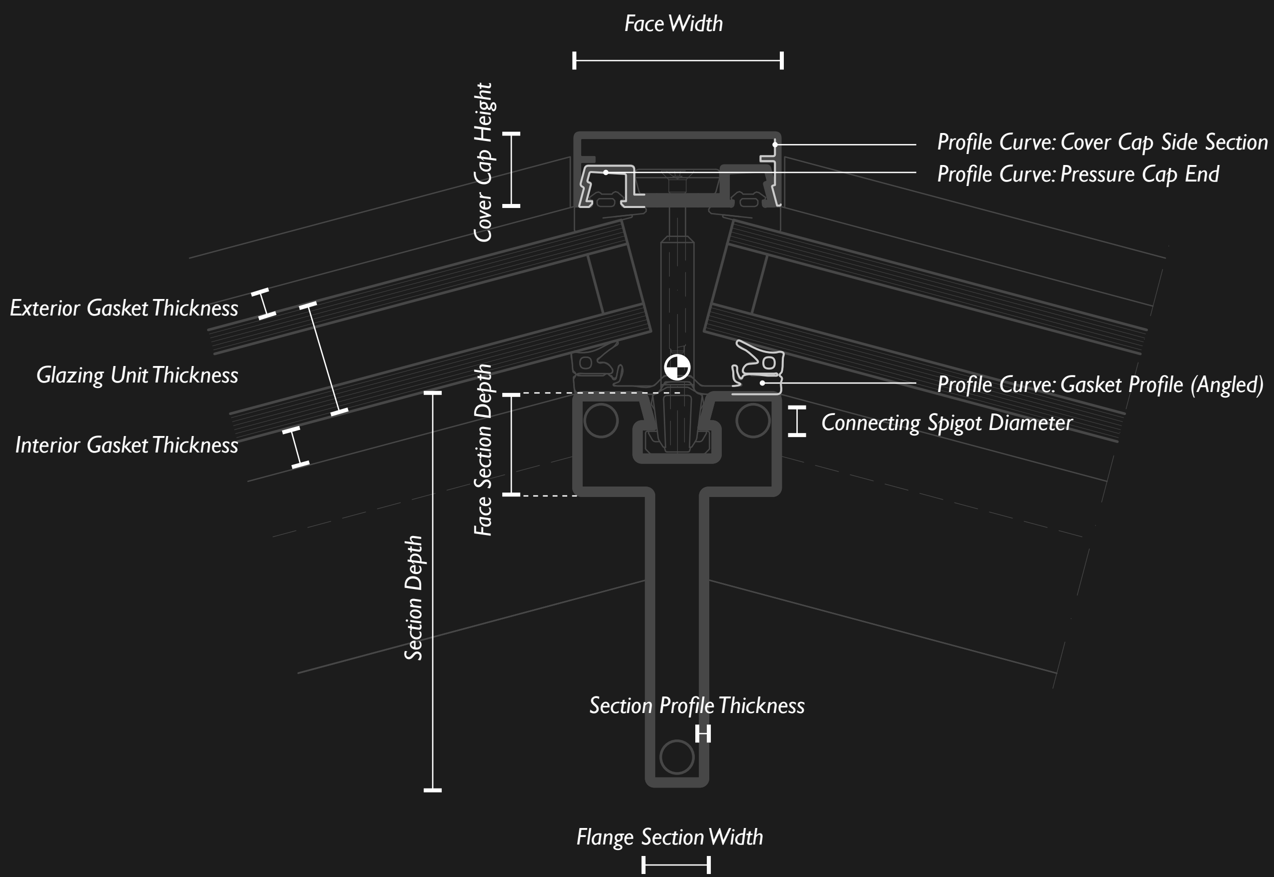


Figure 4.2.2: Definition Input Parameters

4.3
Geometric Logic & Definition

The nature of the geometrical challenges related to free-form facades can be understood by breaking down the elements back into their base geometrical elements, namely planes, surfaces, lines, and points. The primary reference geometry for free-form facades is a Brep surface that is rationalized into a faceted network of planar surfaces as shown in Figure 4.3.1. Each surface is a representation of a cladding element, while each line is representation of the primary structural elements of the facade. The exact relationship between the geometric element and the eventual constructed component can vary. For example, the planar surface may reference the outer face of the cladding element. Alternatively, the line may reference the centerline of the structural element. The relationship can vary depending on a number of factors. Ultimately the selection of which element will be the primary driving element and what the exact geometrical relationship will be is at the discretion of the facade designer. For each node element, a number of incoming curves will intersect at a point. The relative angles between these curves will vary in both U rotation and V rotation (Stephan et al., 2004).

Supposing for this example, that curves are reference geometry for the centerline of the front face of the structural section as indicated in Figure 4.3.2. For any given node, each of the incoming curves, and therefore each of the front-centerlines of the mullions intersect at a single point. This is the geometric ideal for this scenario. While the reference curve represents the longitudinal axis of the mullion, the rotation of the mullion around that axis (W rotation) is typically dependent on the adjacent surfaces (i.e. cladding elements). Typically, the angle of the mullion around its longitudinal axis runs along the bisectrix of the two adjacent surfaces, as shown in Figure 4.3.3.

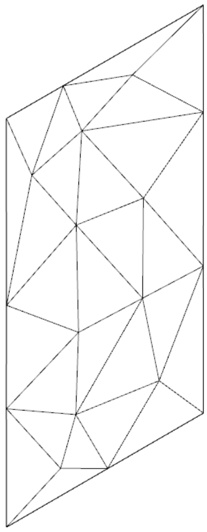


Figure 4.3.1: Primary Reference Geometry

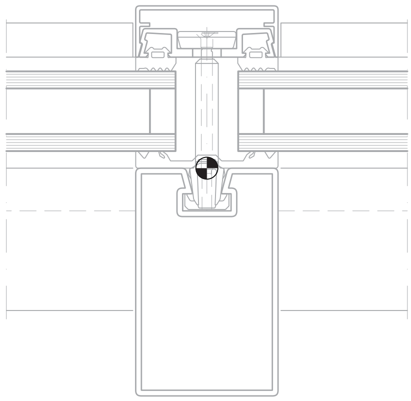


Figure 4.3.2: Typical CW Section with Reference Point

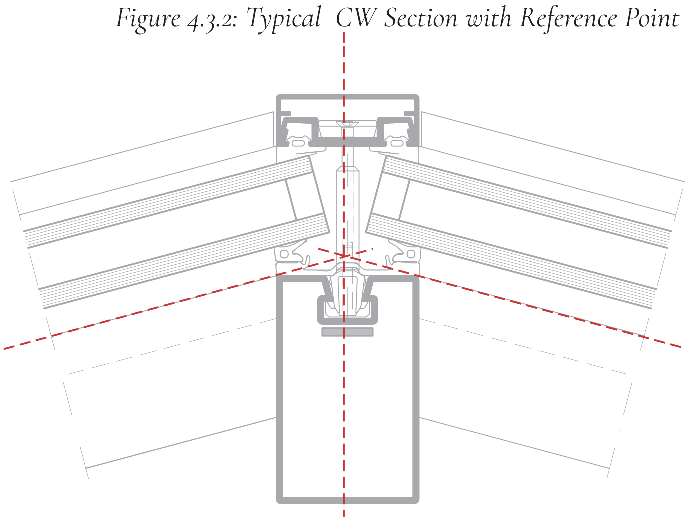


Figure 4.3.3: Typical CW Section Orientation

It is typical that the structural sections for a free-form facade system are of the same depth. While the front centerline of the mullion, in this case, is reference geometry, the back centerline can be understood as dependent geometry, as its location depends entirely on other factors, namely the location of the reference curve and the W rotation of the mullion axis. The distance between the reference curve and the dependent curve equals the local depth of the section. Given the variance in the incoming mullions in U, V, and W rotation, while the reference curves all intersect at a single point, it is almost certain that none of the dependent curve will intersect at all. If we consider the problem in section, with one incoming mullion perfectly horizontal, and two other mullions coming in at different V angles (Figure 4.3.4), we see that the there is no single intersection for all three dependent curves, and that the depth of each mullion, when considered in reference to World Coordinates, is drastically different. While this illustration serves to better understand the challenge in two dimensions, when applied in three dimensions, each of the dependent curves pass each-other in space without every intersecting. This phenomenon also happens in the opposite direction, where the glazing elements, as well as the pressure caps and covers will all be coming in at different angles and World Coordinate depths. Figure 4.3.5 is an illustration of a node with 5 incoming elements from a free-form facade that illustrates the results of directly extruding a section towards a point using the front-centerline as reference curve for the structural member.

This is the root of the geometrical challenge of free-form facades. Firstly, since the facade system relies on an appropriate surface for the installation of air/water/vapour control elements, the different incoming elements need to be resolved in way that does not leave challenging gaps of edges that can hinder the performance and installation of the system. This surface (Figure 4.3.6) is heretofore known as the control surface. Secondly, the geometry is essentially responsible for transferring structural loads, which is both a challenging and unpredictable endeavor.

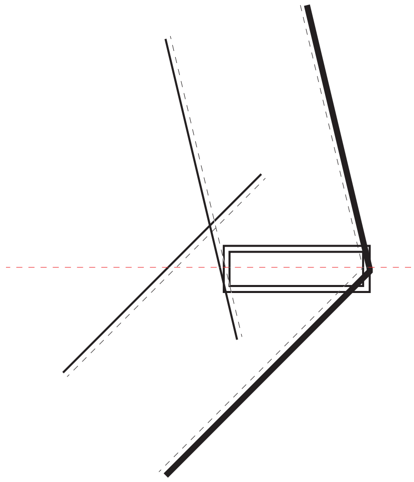


Figure 4.3.4 Geometrical variance between invoming mullions

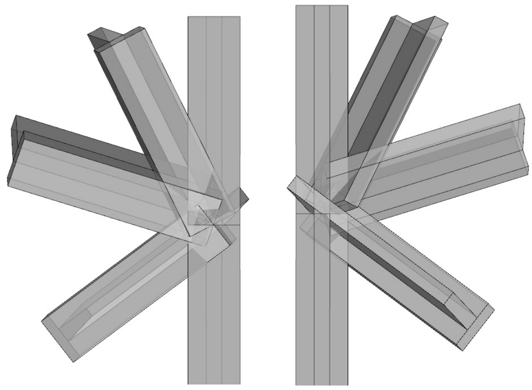


Figure 4.3.5: Simply extruded free-form facade mullions

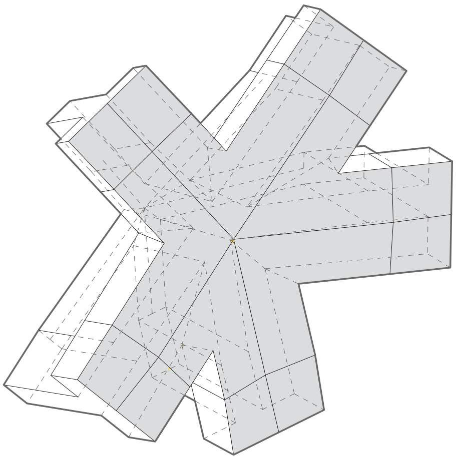


Figure 4.3.6: Control Surface

Geometrical Solution

The definition for the overall geometry works by defining a number of control points that make up the vertices of the main volume. The location of the work-points changes for each curtain wall node, but the general geometrical relationships between the work-points remains the same. These geometrical relationship are what enables the parameterization of the product.

The first part of the definition works by defining the relationships between the work-points, which are used to create lines, which are lofted into surfaces, which are then finally joined into a closed solid. The logic of this definition categorizes the most basic geometrical elements of the node into three categories: Exact, and Restricted and Flexible. Exact Geometry consists of work-points that require a precise location in space, namely the faces of the node where it connects with incoming mullions, as any variance from a precise location might mean a weak or unsightly joint. Constrained work-points are the work-points located on the control surface of the node, which have some freedom in their location, but are restricted geometrically by having to be located in a particular plane, in order to create a control surface that is adequate for the application of the air/water/vapour control layers. The location of these work-points is limited because it directly impacts the performance of the system. Flexible work-points do not have any strictly necessary geometrical requirements, however subjective restrictions are applied in order to achieve a desired aesthetic/feature. Generally, the control surface (the surface on which the air/water/vapour control components are placed) is made up of Constrained work-points. Moving away from the surfaces that directly affect the air/water tightness of the assembly, the geometry becomes increasingly free. Figure 4.3.8 illustrates the fixed and constrained work-points on a typical node. The rest of the work-points on the remaining vertices, omitted for clarity, are flexible.

As an illustrative example, the inner edge between two arms of the node is made up of two work-points: the front work-point near the control face of the node, and the back work-point towards the depth of the node. The front work-point strictly speaking needs to be located at a point on the main reference plane in order to create a smooth surface and adequate space for the quality placement of the interior gaskets. This work-point is a Constrained Work-point. In addition to this, it is desired that the point be located along the axis of the intersection of the intersection mullions such that both incoming face can remain planar surfaces, which is a (subjective)design decision, but not pertinent to the performance of the system. The back work-point should also be located along the same intersection axis to maintain the planarity of the incoming edges. The exact location of this point is defined by the furthest point along the axis on the incoming surfaces, such that the depth of the section only increases, and never decreases. Again, these are design decisions that are not pertinent to the performance of the system. The back work-point is Flexible.

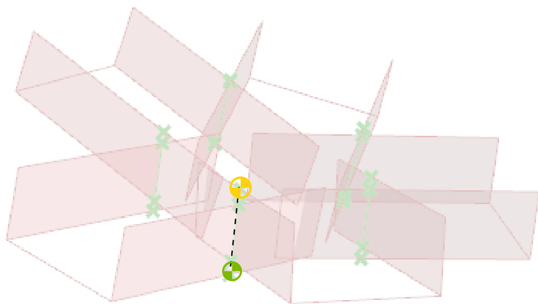


Figure 4.3.7: Control points at mullion intersection

As such, the main reference planes are located on the control surface of the mullions, which consists of Restricted geometry that easily and rationally converges at a single point. Moving away from this surface in section, work-points generally become increasingly flexible. Figure 4.3.9 illustrates an representative sample of work-points and their categorization in a typical section through a node arm.

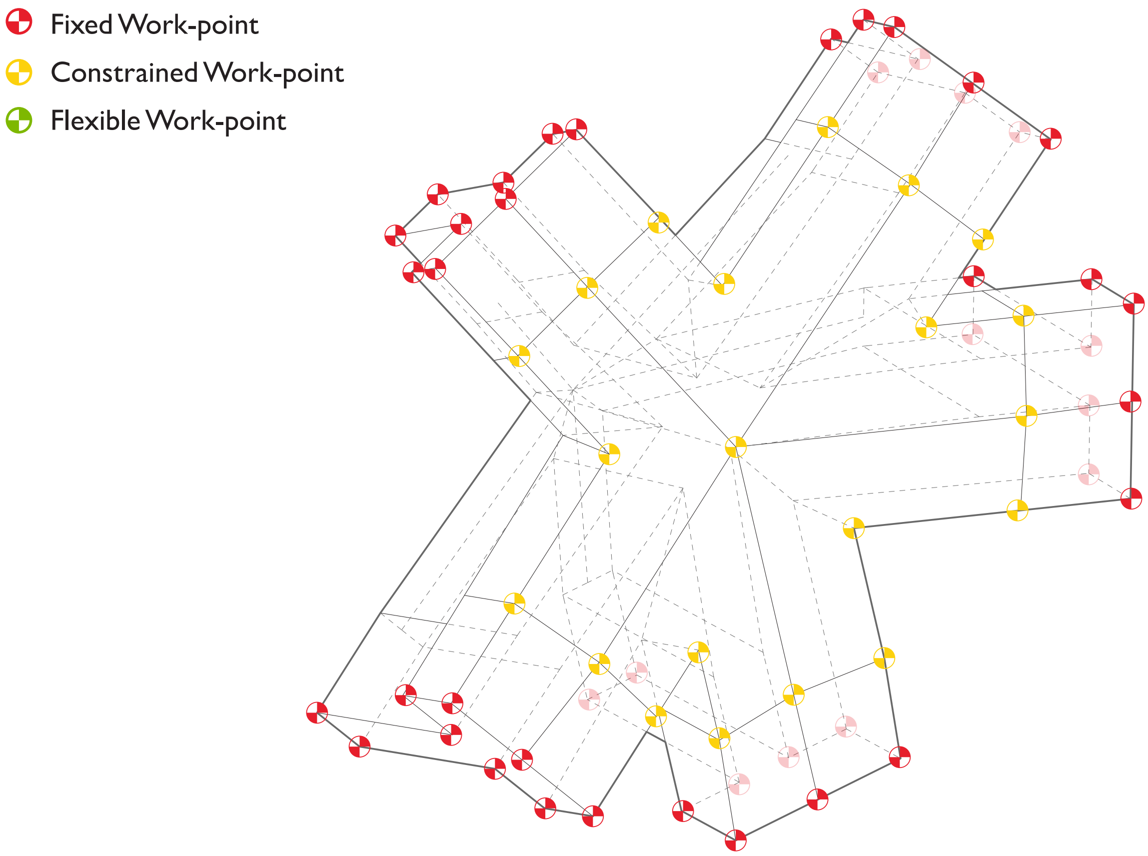


Figure 4.3.8: Fixed and Constrained control points on typical node

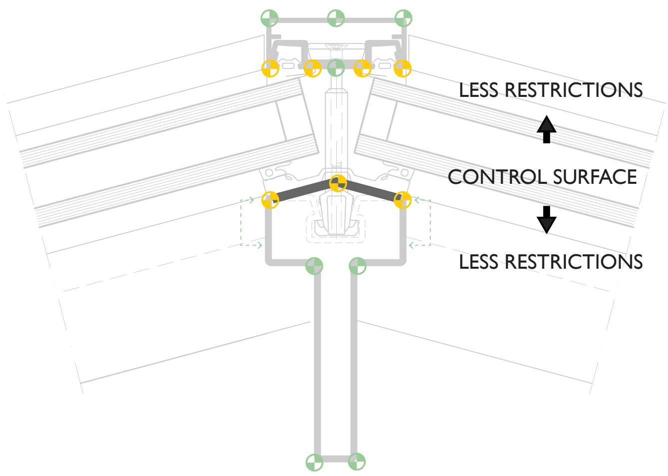


Figure 4.3.9: General logic for control point definition in section

The main structural part of the node is divided into two zones: The Inner Zone and the Transition Zone (Figure 4.3.12). The purpose of the transition zone is the length in which the section of the node arm transitions from a section that matches the incoming mullion (Figure 4.3.10), to a similar section whose top edge is faceted so that each facet edge is parallel to its respective cladding element (Figure 4.3.11). The reference curve, which is illustrated in Figures 4.3.1 runs parallel to the mullion through the peak of the Transition Plane Section top edge.

The Linea Profile that is used is a specialized T-shaped hollow profile with the standard Jansen VISS system groove along the front centerline to accommodate the insulated studs and glazing supports. The wide end of the section which comprises the control surface is important for both structural and control layer performance. The narrow end of the section, on the other hand, only serves a structural purpose, adding to the stiffness of the profile.

Geometry Definition

This section describes the geometric logic for the definition of the primary components in the assembly. The base definition generates in detail the main node volume, pressure plate, and cap for the node. It also generates rough geometry for the interior and exterior gaskets. Due to the limited time-line of this project, and the limited availability of appropriate printing technology for these components, they are not defined in great detail and will not be discussed at length in this section.

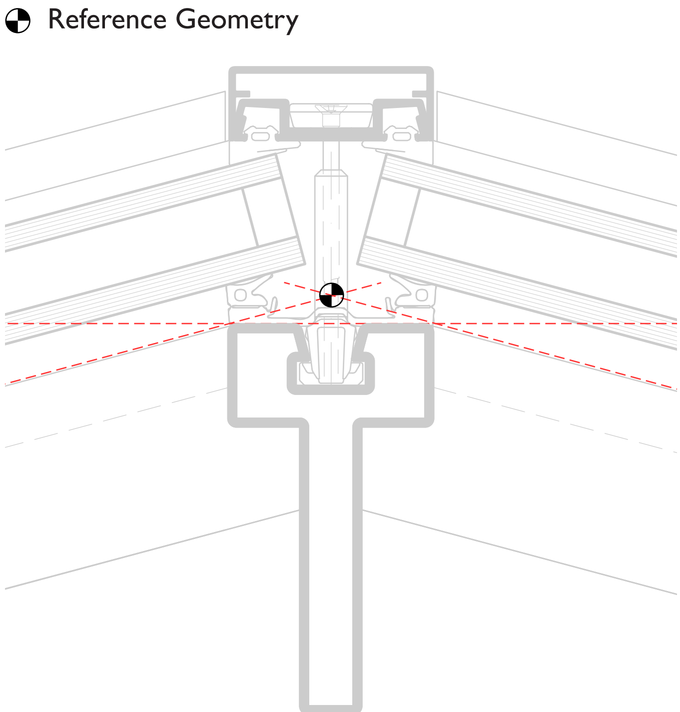


Figure 4.3.10: Section @ Attachment Plane

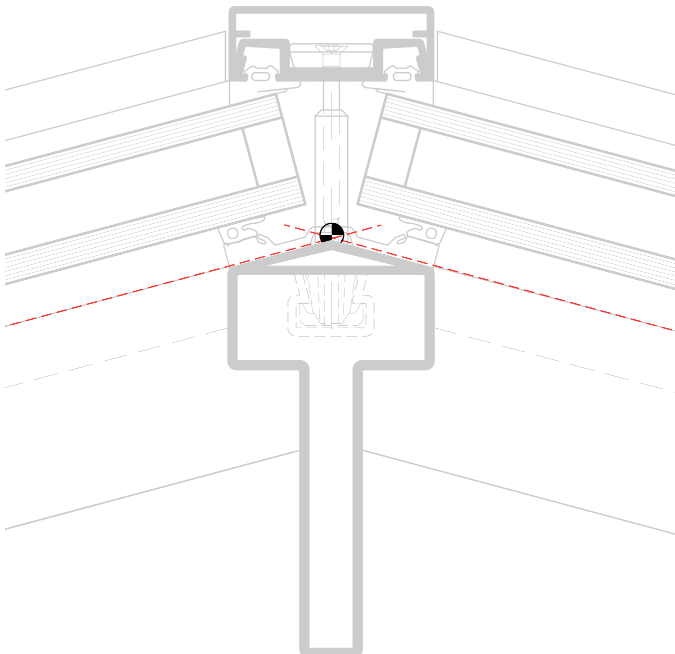


Figure 4.3.11: Section @ Transition Plane

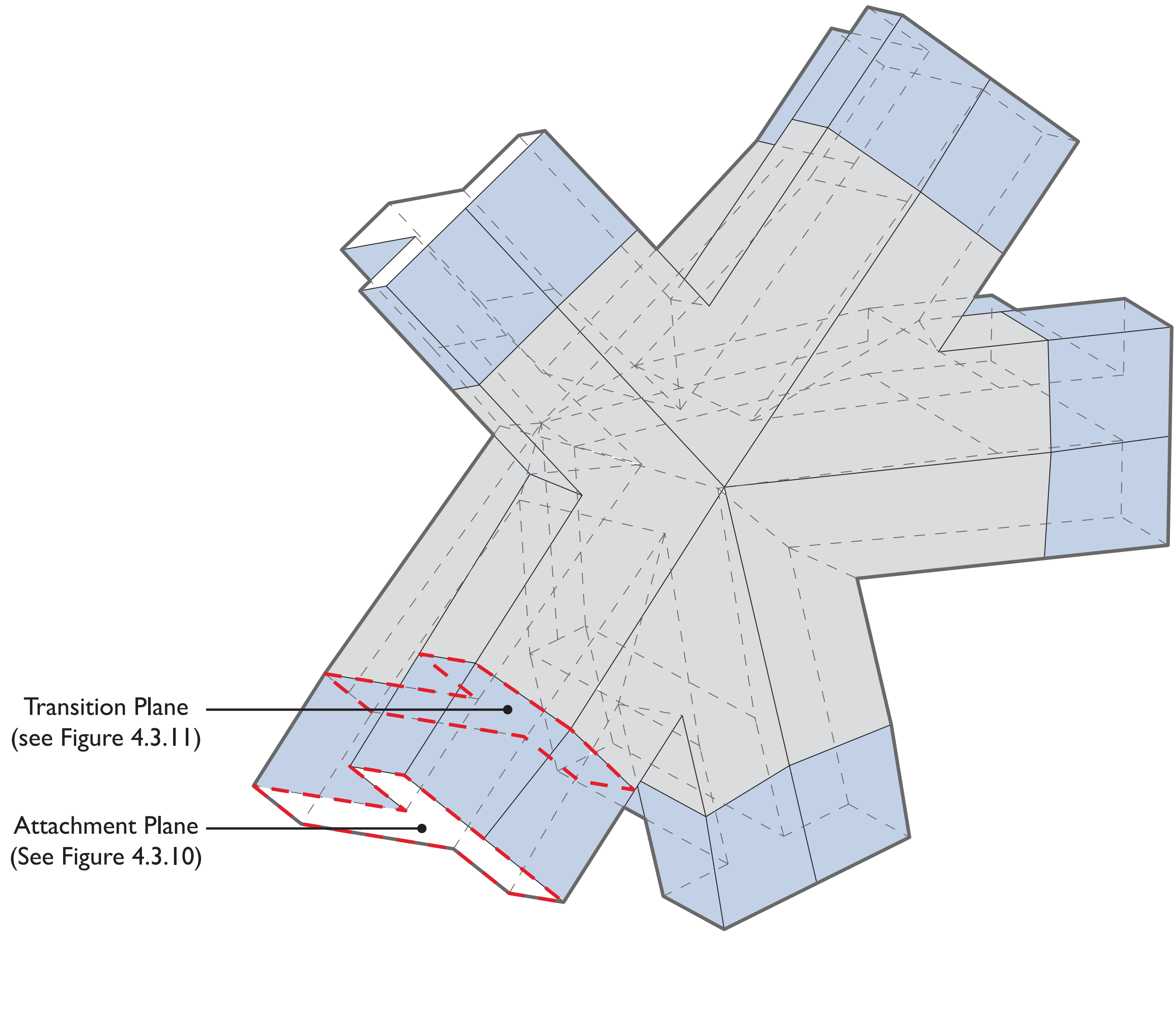
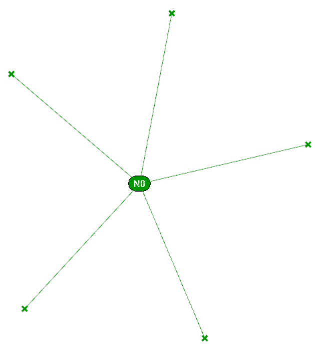
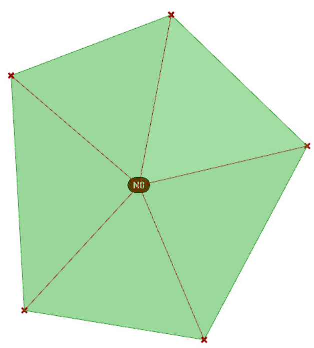


Figure 4.3.12: Relative location of attachment plane and transition plane on trypical node arm

1. BASE GEOMETRY - The input for the node definition is a number (3 to 6) of lines coming into a single point. These lines are heretofore referred to as Primary Lines. Primary Lines are generated from the definition for the overall geometry of the wall, which will vary from project to project. Primary Lines run in the direction of the incoming mullions. Each line is configured so that its start point is at a distance of 0.2m from the center node. As the maximum dimension for most cost-effective printing beds is in the 30 to 40 cm length/width range, 0.2m from the center represents the maximum extent of the node. The end point of the Primary Lines converge at a single point which represents the main work-points for the overall geometry, heretofore



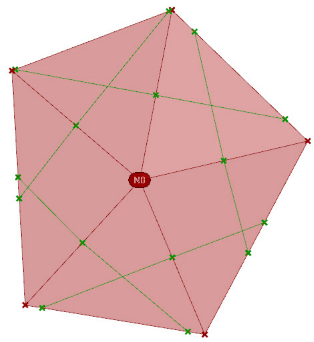
2. Primary Lines are used to generate surfaces that are planar to the cladding elements, heretofore referred to as Main Reference Planes. These planes/surfaces converge at the Apex.



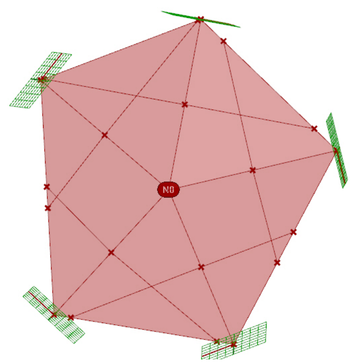
3. At the center-point of each Primary Line, a perpendicular plane is generated and used to generate sections through adjacent surfaces. The sections are translated into unitized vectors. The average of these vectors represents the y-axis vector for the incoming mullion, consistent with the typical detailing of the assembly for angled facades.

► IF the node is on the perimeter of the wall and therefore reference curves only have one resulting vector, plane is defaulted to be aligned with world Y Axis

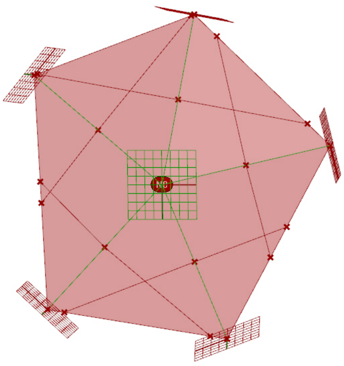
► The system limitation for angles between adjacent panels in the existing system is 30° (15° on both adjacent planes from mullion centerline). The definition uses these vectors to measure the angle between adjacent planes. If one of these angles exceeds the limitation, the definition will still function, but this will flag a message noting that the angle is outside of the system limitations.



4. These vectors are used to generate the base planes for the incoming mullions.

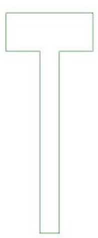


5. Primary Lines are translated into vectors, heretofore referred to as **Primary Vectors,** and summed together. This vector is used with the Apex to generate a panel from a normal vector and origin, respectively. This plane is heretofore referred to as Apex Plane. The normal vector of this plane is used as the primary depth direction of the node. This vector is heretofore referred to as **Node Normal**.
► IF the node is on the perimeter of the wall, the plane is automatically oriented parallel to World XZ plane.

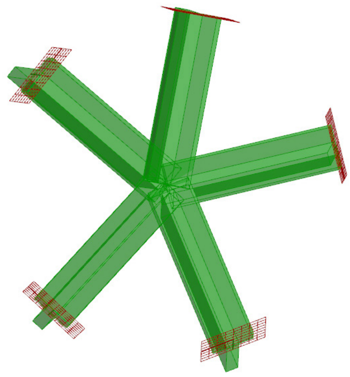


6. MAIN NODE GEOMETRY - Profile sections are generated on the base planes using following profile parameters for Linea Profile:

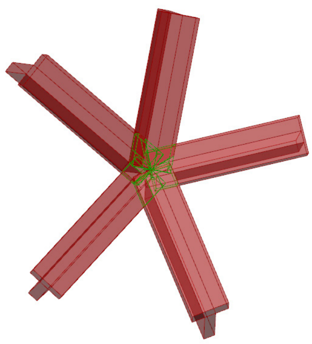
- ► Total section depth
- ► Upper portion depth
- ► Upper portion width
- ► Lower portion width
- ► Section thickness
- ► Corner radius
- ► Connector Radius



7. Profiles and base planes are moved along local Y vector such that the upper corners of the profile are located on Main Reference Planes. Updated planes heretofore referred to as **Primary Planes.**

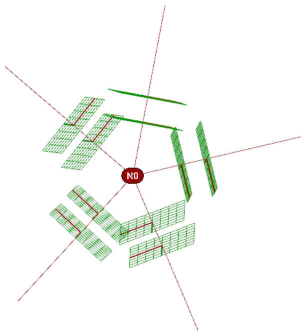


8. Profile sections are extruded along the Primary Vectors to Apex. Each mullion Brep is intersected with the adjacent mullion Brep. The resulting volume is deconstructed and evaluated to extract the furthest point from the Node Normal. This point represents the minimum distance from the node that the arm of node can stretch in order to avoid more complex than necessary geometrical resolution. This distance is heretofore referred. A parameter is made available to add a discretionary length to this number, the sum of which is heretofore referred to as Minimum Arm

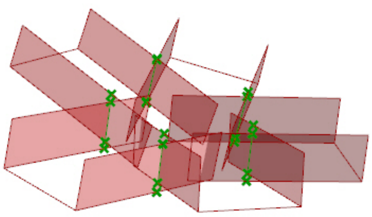


Length.

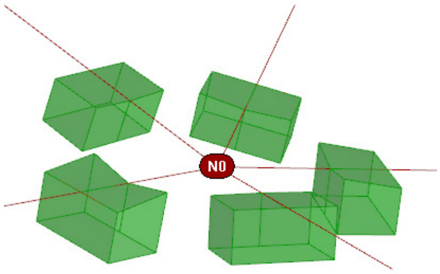
9. Primary Planes are relocated be at Minimum Arm Length from Apex. These planes represent the end of the transition zone. Planes are offset by a user-defined parameter representing the depth of the Transition Zone: the zone that morphs in profile from the standard mullion section to an adapted mullion section. The former plane is heretofore referred to as the Inner Plane and the latter as the Transition Plane.



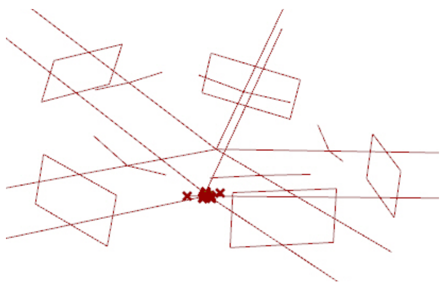
10. The edge surfaces of each incoming mullion are extruded towards center. And intersected with the adjacent extrusion. This line represents the location of the inner edges of the node arms. The front point of the line is extended to that it extends up to the Main Reference Planes and creates a planar control surface on the front face of the node. The back point is extended to the furthest point along the line on either one of the intersected surfaces in order to always increase, and never decrease, the section depth of the profile.



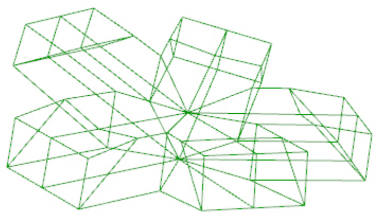
11. Profiles are generated on both the Inner Plane and the Transition Plane. The profiles are divided into two rectangles - one that represents the upper half of the section with the control surface, and lower rectangle that represents the long narrow flange of the section profile. The profile on the Inner Plane is identical to that on the Transition Plane, except that its topmost edge is faceted to touch at a point its respective Primary Line. The Transition zone is such that its upper surface transitions from being planar to the incoming mullions, to being planar to the Main Reference Planes.



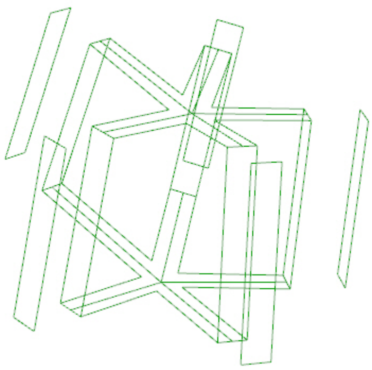
12. For the upper rectangle, a line is drawn from the bottom edge of each profile on the Transition Plane, along the Primary Vectors. The Transition Plane is used because the geometry of the transition zone on the interior face of the node does not matter and this creates a smoother geometric transition. Although these curves do not intersect, the curve proximity tool is used to pull the closest points between curves, and this point cloud is averaged to create a single point. This point is heretofore referred to as Division Point because it divides the upper and lower portion of the section.



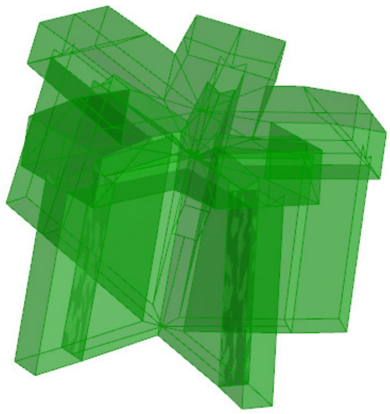
13. A line is created from midpoint of curves to Interior edges are connected back to profile edges. Curves generated thus far create wire-frame for upper volume of the node which are used to generate solid Brep.



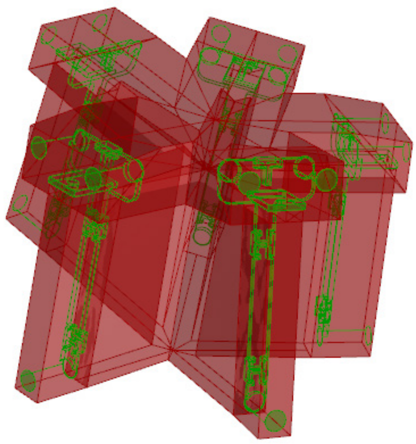
14. For the lower volume, a similar strategy is used, however only using The Inner Plane. The profiles on the two planes are then lofted together to create the lower portion of the transition zone, which must be kept planar to house the integrated connection piece.



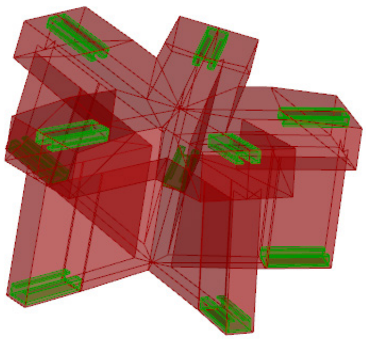
15. The top and bottom parts are joined together to form the main volume for the main structural member of the curtain wall node. This volume is exported to STEP file for further processing in SolidWorks.



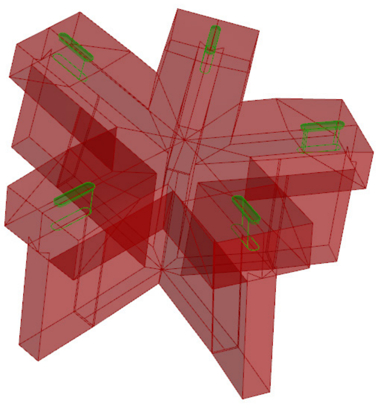
16. The geometry for the connection pieces is generated inside the transition zone of the node. The specifics of this geometry will be elaborated on in a further section. The geometry includes the connections pieces themselves as well as the rails that the connection piece will use to slide into position. A printing tolerance of 0.5mm is provided to enable space between the integrated parts and the main node.



17. Female part of rails are generate connectors and connecting back to the shell of the main node geometry. These rails also provide 0.5mm of printing tolerance for movement.



18. A volum representing the boolean negative for the slotted hole at the top of the node along the range of motion of the interior connectors is also generated.



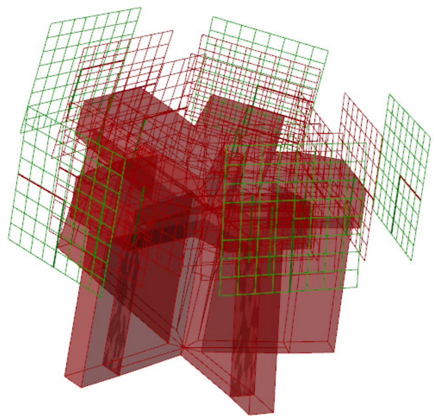
19. EXTERIOR COMPONENTS - The exterior part of the system is defined similarly to the interior part of the system, except that there is a third zone, the attachment zone, which overlaps with the incoming mullion so that the pressure caps can be fastened using the thermally broken insulating studs which fit into the typical mullions. Typically the location of these studs is determined by the following equation:

(a - 200) / 150 = result

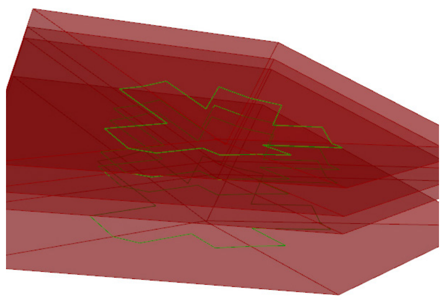
Decimal place of result x 75 + 100 = Edge distance y

Where: a= centerline distance between mullions

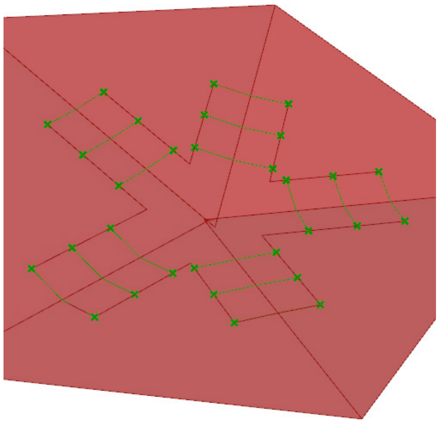
Edge distance y= distance of stud from centerline of mullion



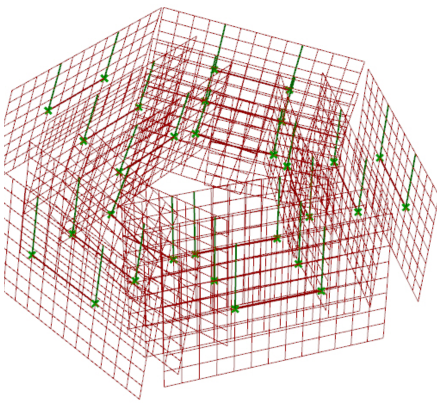
20. A number of planes, offset from the main Reference Planes are generated to create base geometry for the outer components.



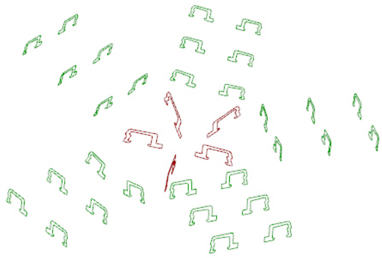
21. The top of the mullion geometry is projected onto the "Base of Pressure Cap" surfaces and subsequently intersected with the three planes: Inner Plane, Transition Plane, and Attachment Plane. This generate three curves that help the local orientation of the components.



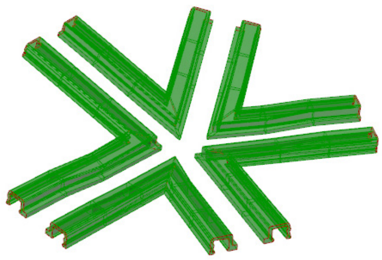
22. A copy of each plane is made at either end of each of its respective curves, oriented so that the x axis of the curve is aligned with the direction of the curve segment on which is located, and slanted so that the y axis runs in the direction of the normal vector for the node. This is because the profile sections that will be generated on these planes will be used to generate parts of a snap-fit connection that will run along each one of the node arms, therefore the grooves must all be ixed together in the same direction.



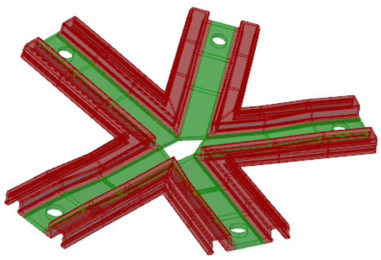
23. PRESSURE PLATE - on each of these planes, a copy of the pressure plate profile segment is projected. In addition to this, another plane that is the average of each set of adjacent planes is generated, and the profile on the Inner Plane is Projected onto this plane.



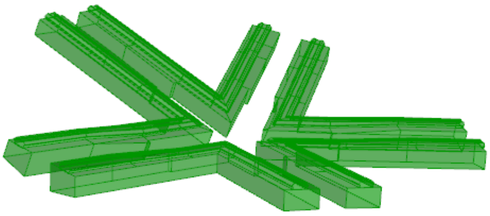
24. The section profiles are lofted together to generate part of the pressure plate profile.



25. The edges between the pressure plate pieces are connected together with solid planar geometry, and then a 5mm radius hole is created in the middle of the attachment zone so that the piece can be attached using insulated studs on the incoming mullions..



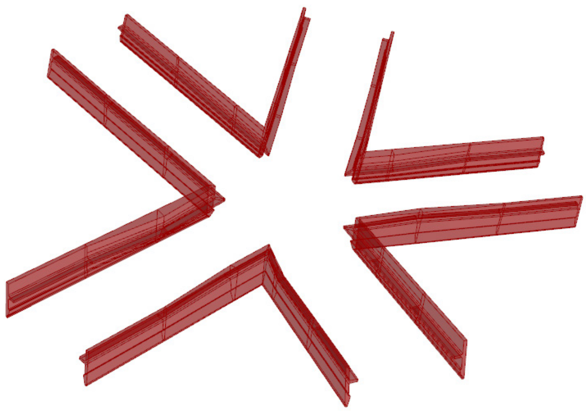
26. EXTERIOR GASKETS - Outer Gaskets are generated using a logic and reference geometry similar to the Pressure Plates. A profile section is used to generate the protrusion that fits into the pressure plate for a connection. The rest of the gasket in this definition is only schematic - it's outer face running always planar to and adjoining the inner face of the pressure plate, and its inner face planar to and adjoining outer the face of glass.



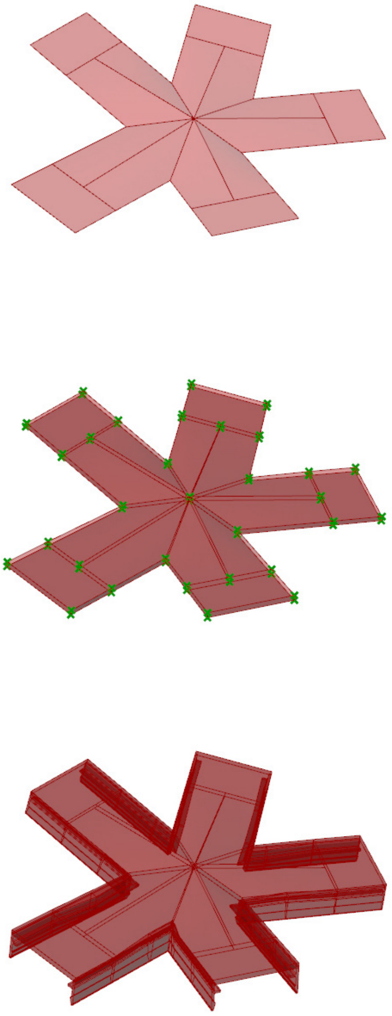
27. INTERIOR GASKETS - Interior gaskets are also generated schematically. For each major part of the gasket , the inner face runs planar to and adjoins the control surface of the main structural part of the node, and the outer face runs planar to and adjoins the inner face of glass. These part of the gasket are connected by a thin flat connection the maintains the water barrier between glazing elements and protects the sreel from moisture exposure. a thin protrusion is also added at the end of each arm of the gasket to lap with the gaskets of the incoming mullions in order to provide a continuous water barrier.

28. CAPS - Cap profiles are oriented on same planes as pressure plat profiles. Cap profile omits outer edge curve. Thi curve is generate at each oriented curve so that the outer edge of the section always remains parallel to the main axis of the mullion.

29. The section profiles are completed, closed, and lofted according to the same principles as the pressure plates to create the arms of the cover cap, which will eventually connect with a snap-fit connection to the pressure plate.



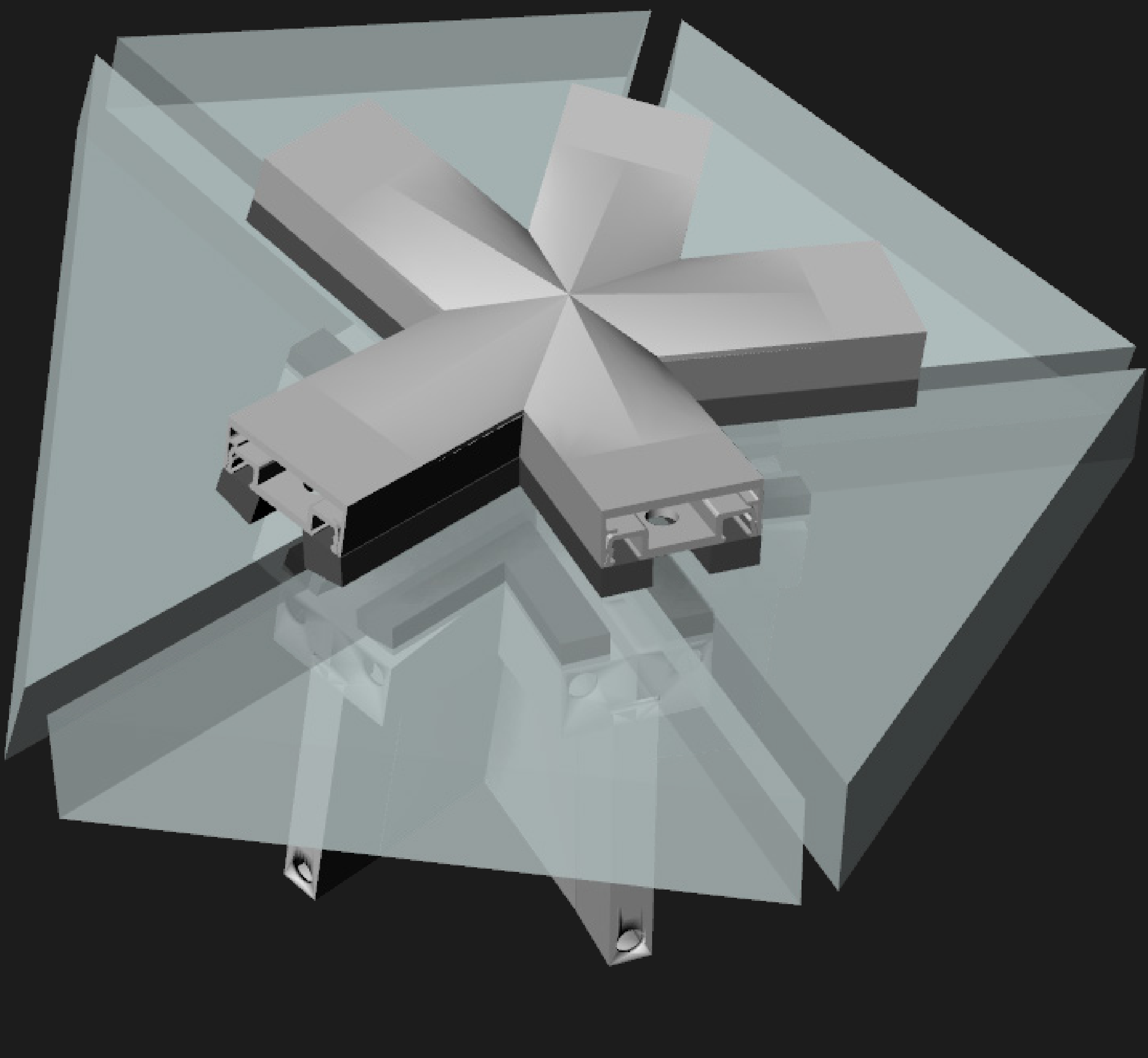
30. The upper surface of the cap is generated with a flat surface in the attachment zone, and faceted surfaces that converge at a single point. This surface is regenerated at an offset of 3mm using perpendicular vectors and cross product to create the upper face of the Cover Cap. The upper and lower volumes of the cover cap are merged together to form the cap geometry.



FINAL GEOMETRY - Due to the shortcoming of Rhino/Grasshopper to effectively perform a number number of necessary operation, namely the generation of a closed shell with an even thickness, and a number boolean operations, the geometry generated in Rhino/Grasshopper as described in this section is exported as a STEP file and brought into solidworks for further processing in order to generate ready for printing components. Solidworks is a powerful tool that uses a combination of Brep and Constructive SOlid Geometry (CGS) enabling a number of feature-based modeling approaches (Gibson et al., 2015). This tool maintains "adjacencies amongs all points, curves, surfaces, and solids" (Gibson et al., 2015), enabling more reliable and successful geometrical operations between complex Breps than Rhino/Grasshopper.

The final components are illustrated with their main design features in the next section. The digital files used to generate the graphics in the next section are the necessary deliverables for the fabrication of these parts.

4.4
Nodable Design & Features



Nodable Assembly Components

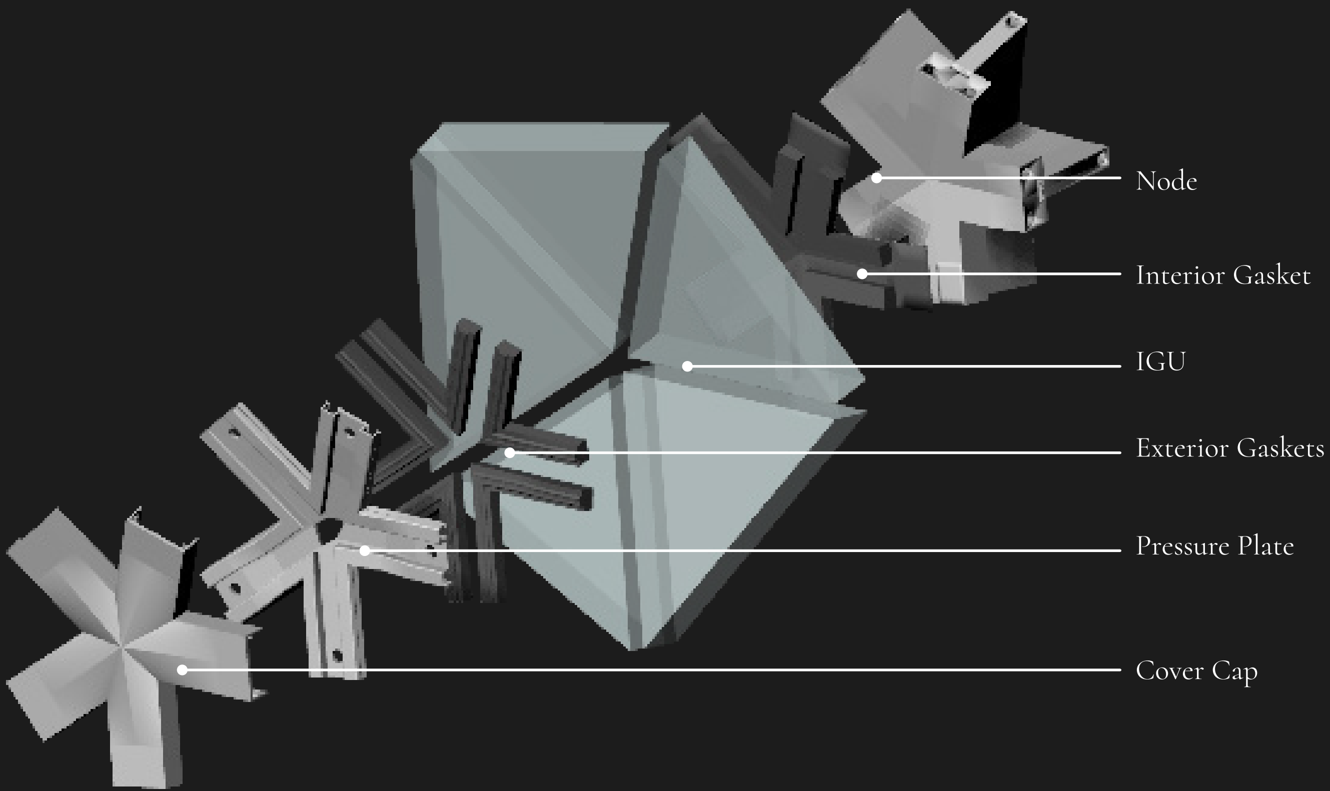


Figure 4.4.1: Nodable System

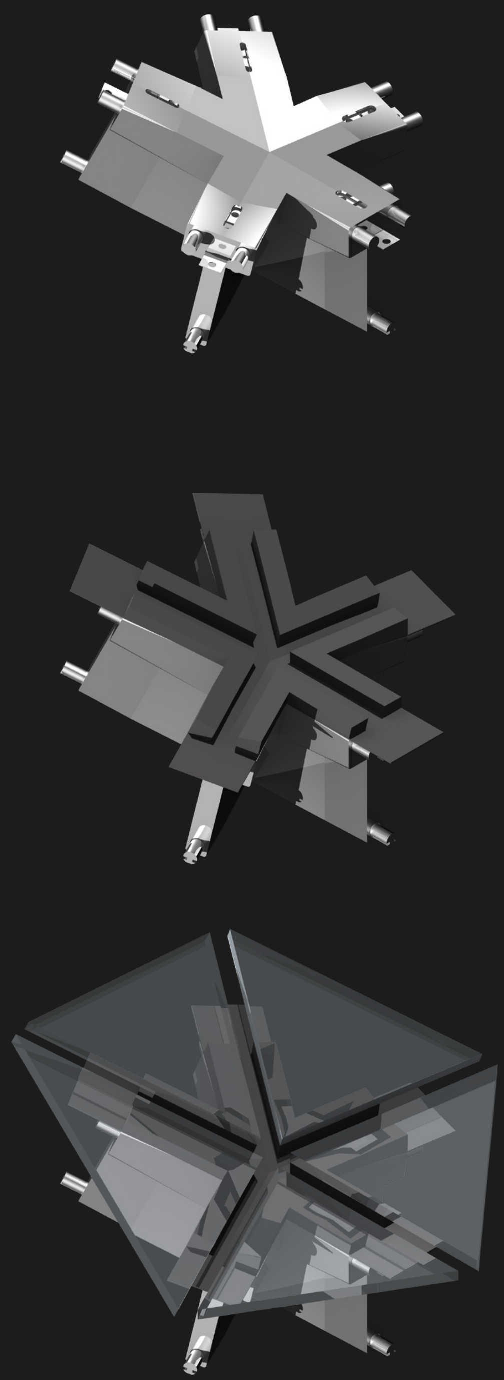


Figure 4.4.2: Nodable System

Section Details

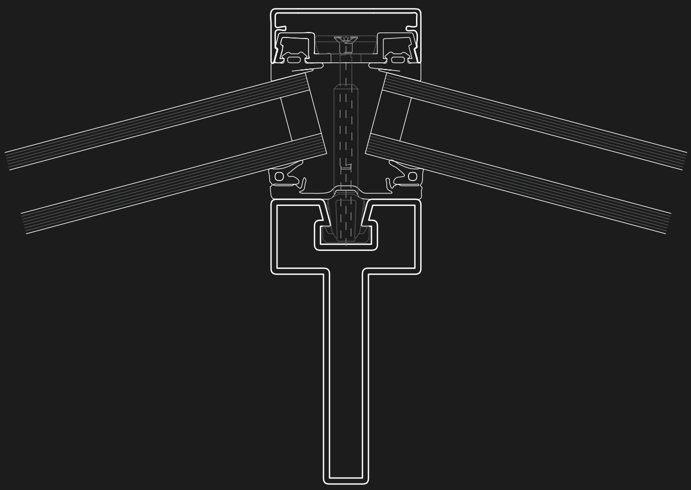


Figure 4.4.3: Typical VISS system vertical section (convex glazing)

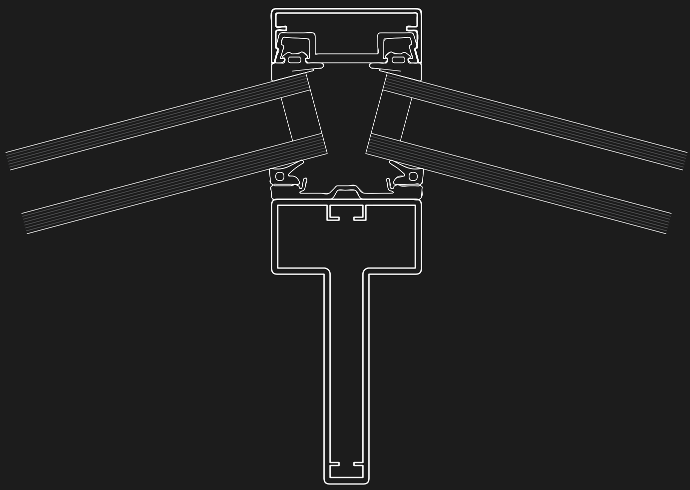
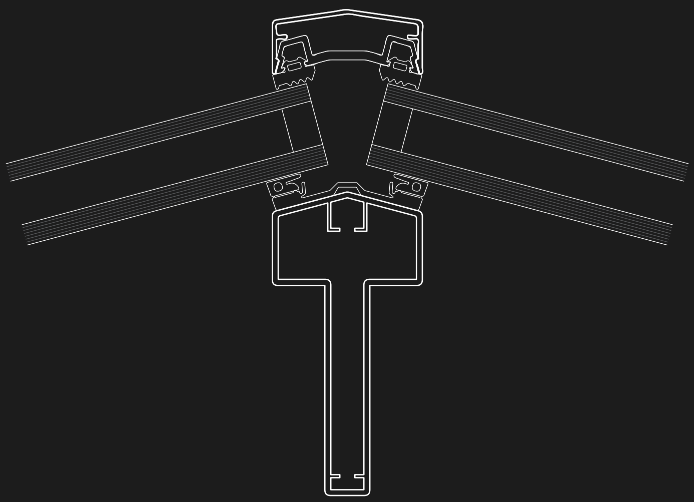


Figure 4.4.4: Nodable section @ start of transition zone (convex glazing)



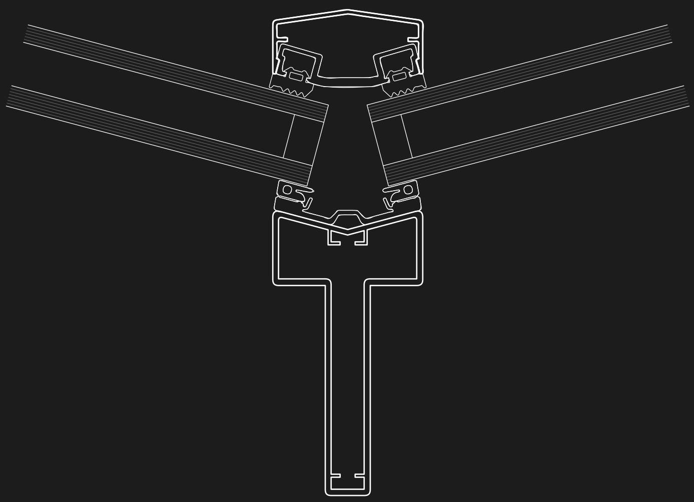


Figure 4.4.5: Nodable section @ end of transition zone (convex glazing)

Figure 4.4.6: Nodable section @ end of transition zone (concave glazing)

Hypothetical Wall Example
Generated Nodes

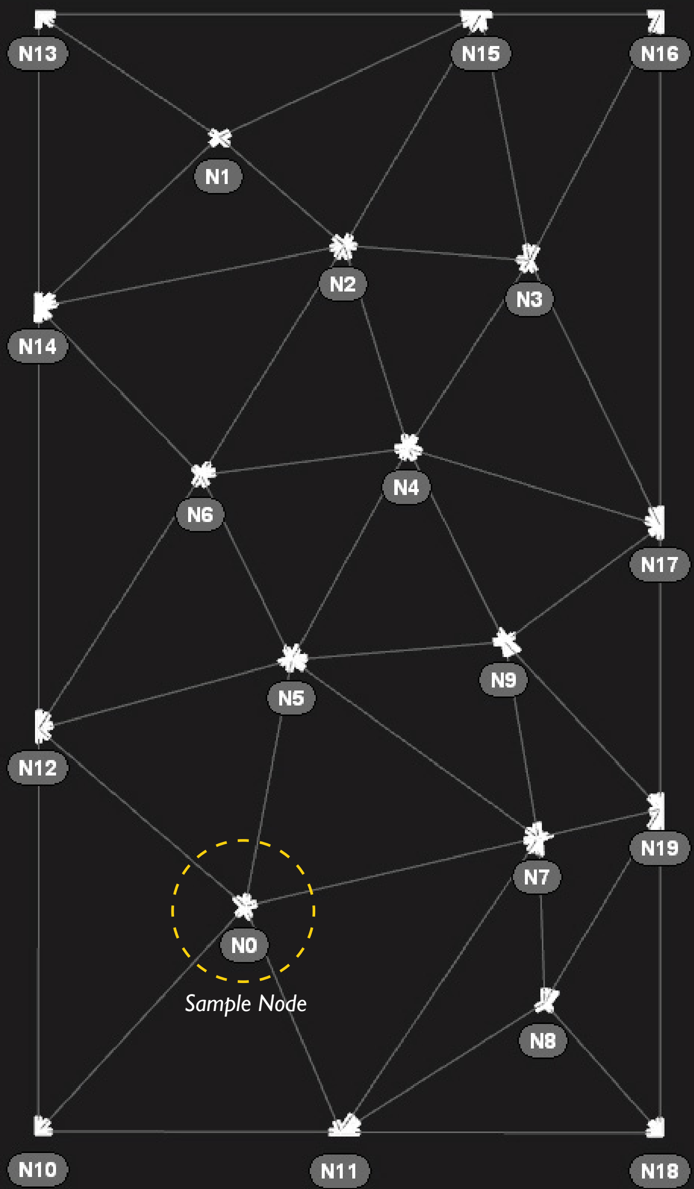


Figure 4.4.38: Node Base Geometry for hypothetical wall assembly - Wall Dimensions 3mx9m

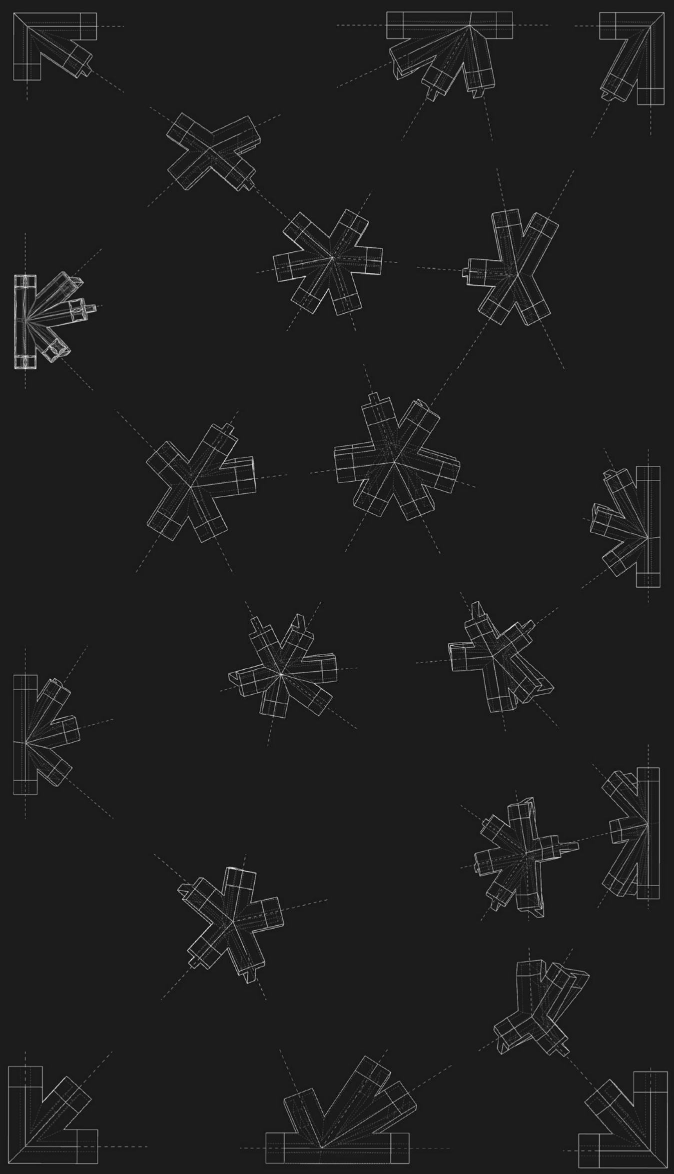


Figure 4.4.39: Node Base Geometry for hypothetical wall assembly - closeup

Nodable Base Design Main Body

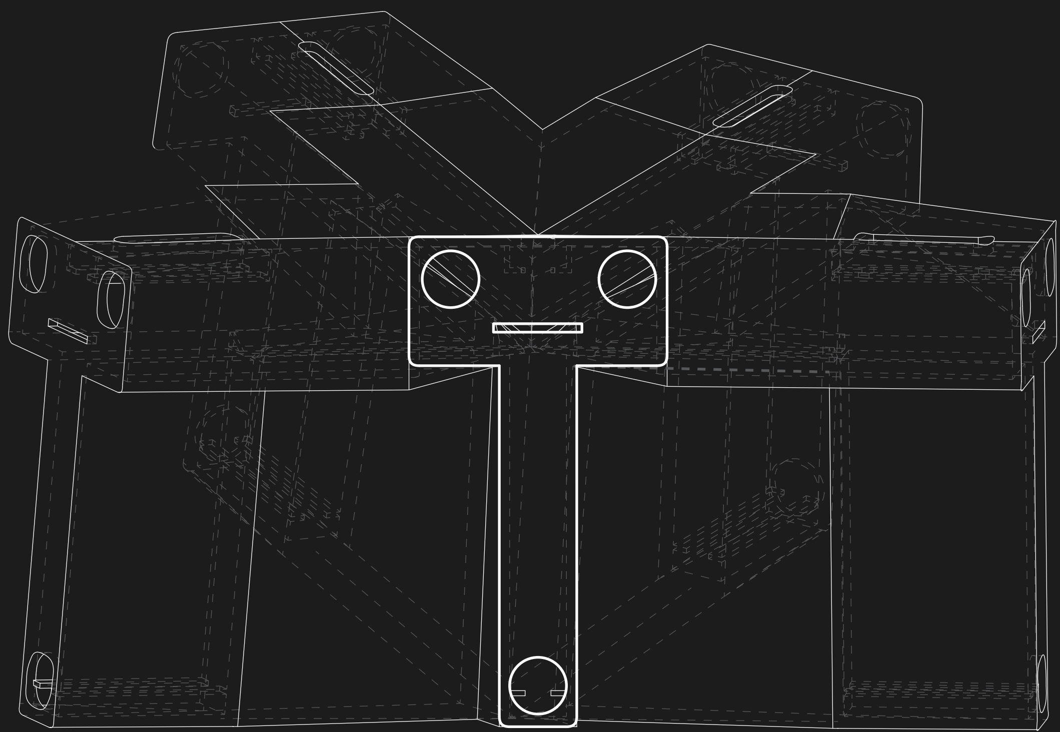


Figure 4.4.7: Main Body Front View

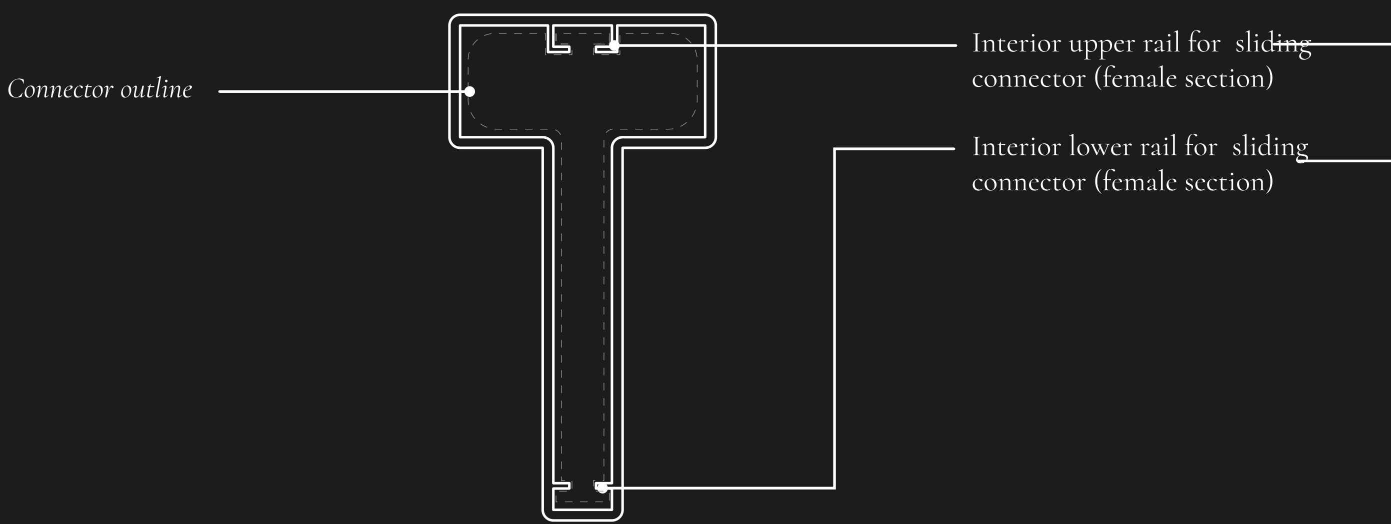


Figure 4.4.8: Main Body Section Through Typical Node Arm

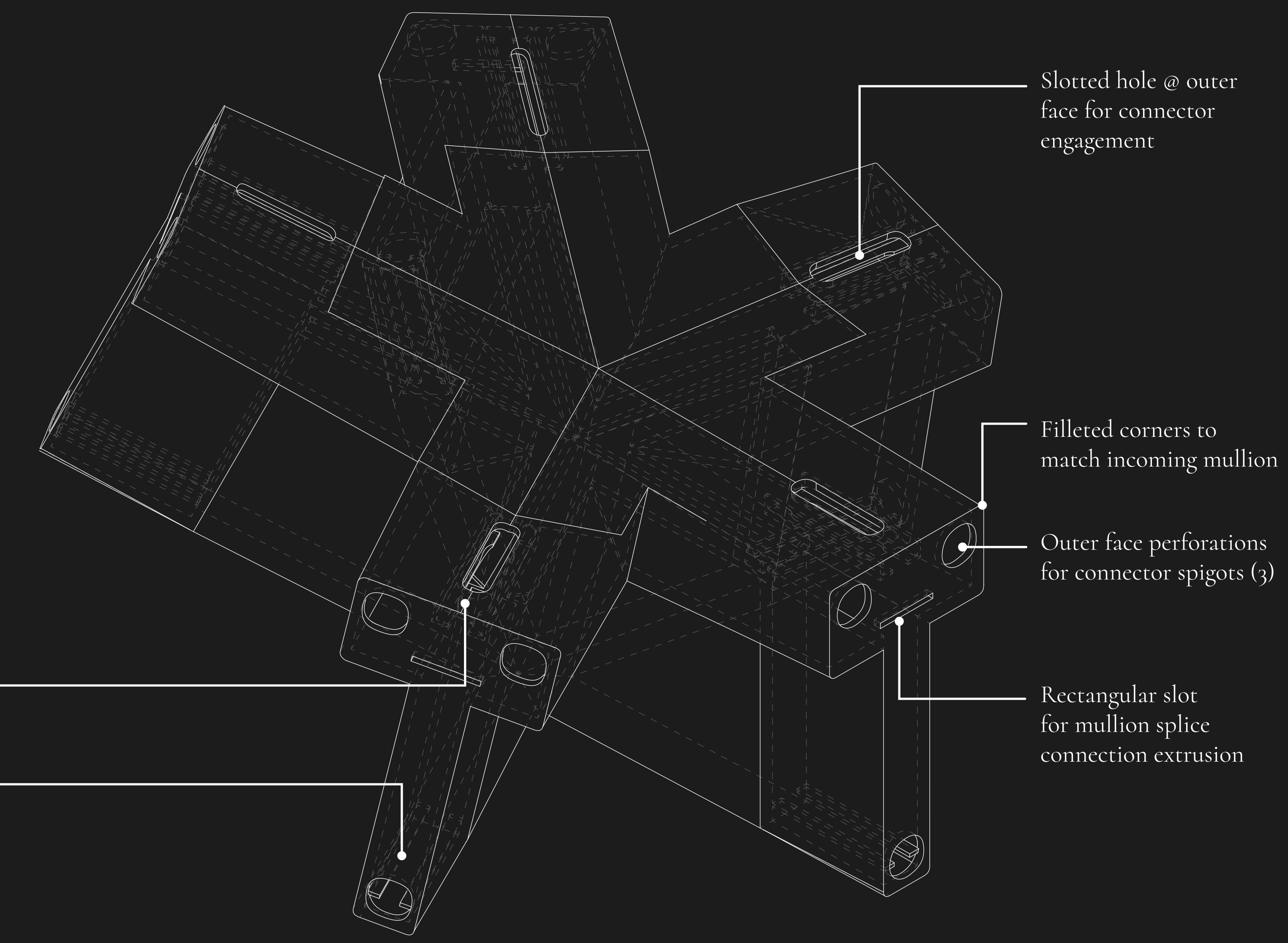


Figure 4.4.9: NMain Body Isometric

Connector

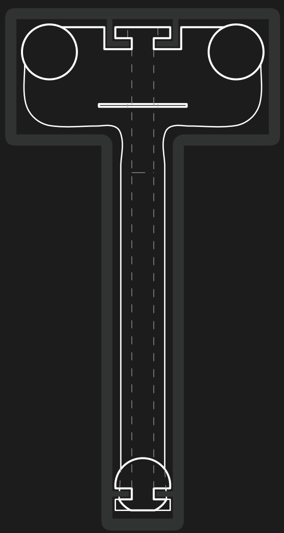


Figure 4.4.10:
Connector Front view

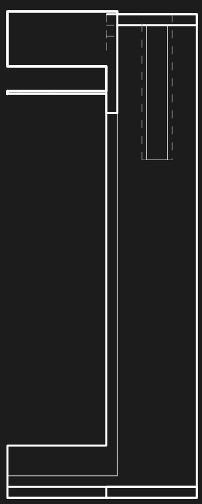


Figure 4.4.11:
Connector Side view

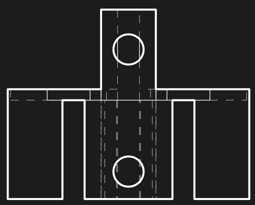


Figure 4.4.12:
Connector Top View

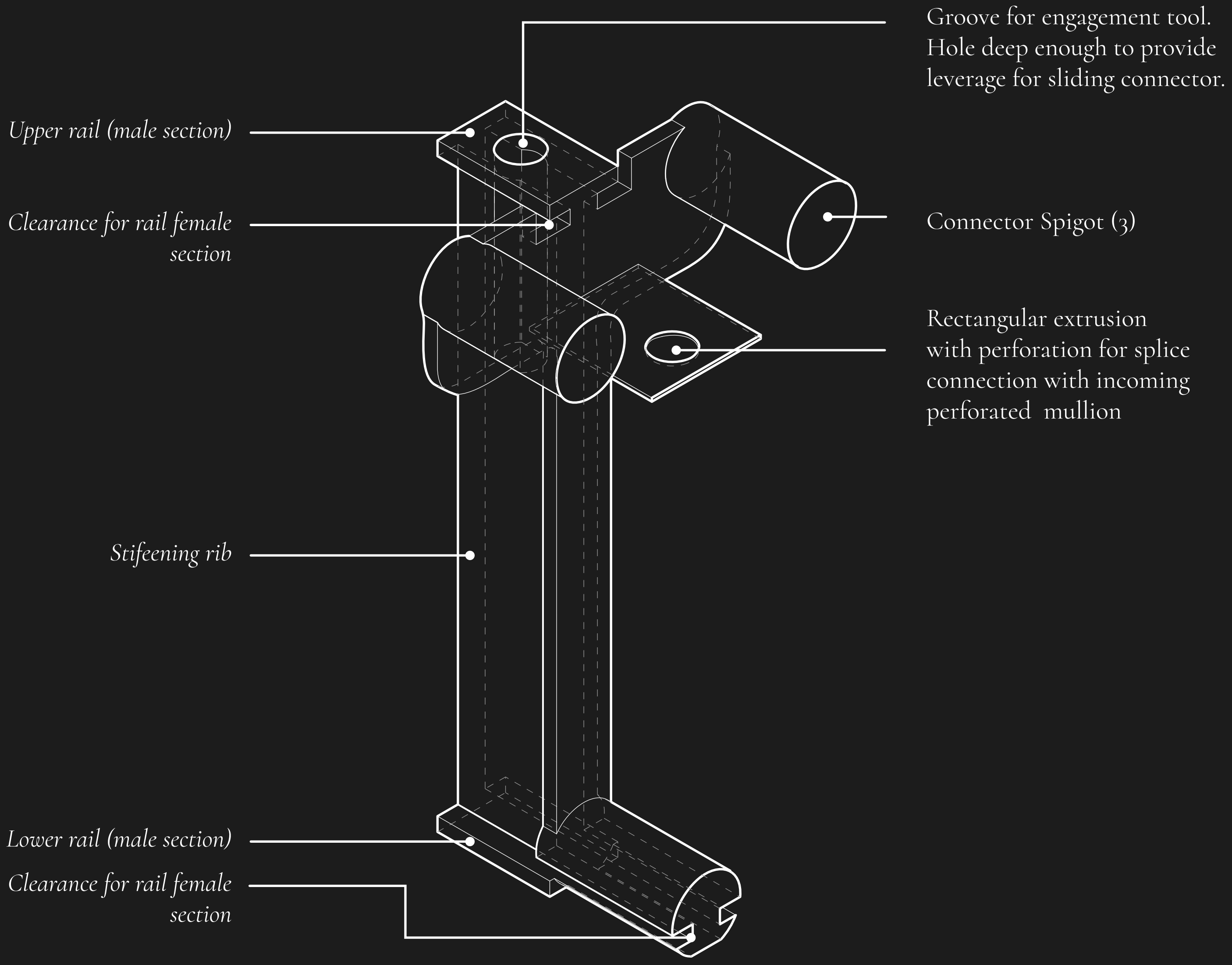


Figure 4.4.13: Connector Isometric

Nodable Interior Gaskets

Figure 4.4.14: Interior Gasket Section A

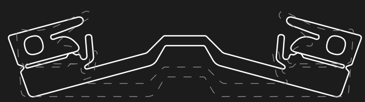


Figure 4.4.15: Section B: Concave Glazing

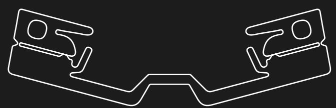
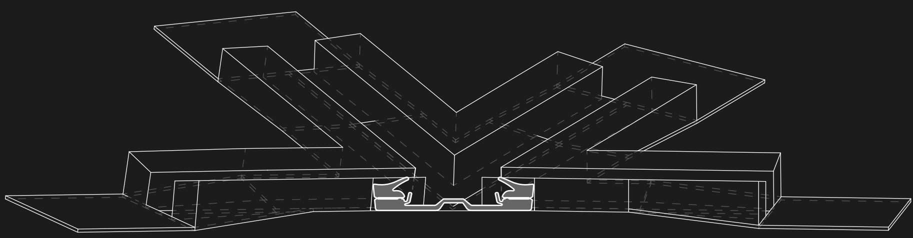
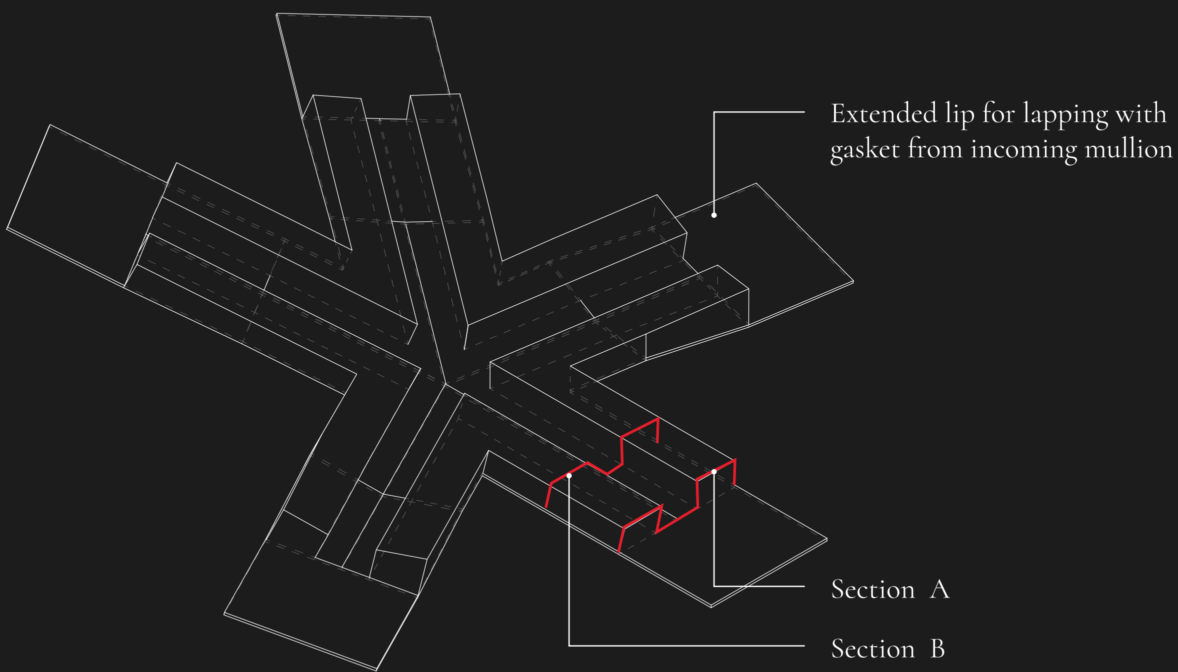


Figure 4.4.16: Section B: Concex Glazing



Fugure 4.4.17: Interior Gasket (schematic) Front view



Fugure 4.4.18: Interior Gasket (schematic) Isometric

Nodable Exterior Gaskets

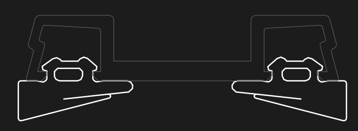


Figure 4.4.19: Section A:

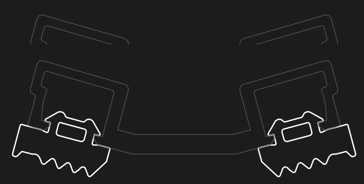


Figure 4.4.20: Section B: Concave Glazing

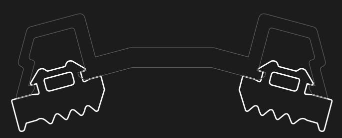


Figure 4.4.21: Section B: Concex Glazing

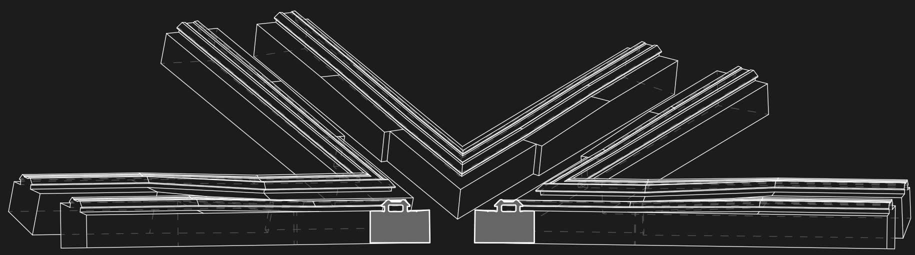


Figure 4.4.22: Exterior Gasket (schematic) Front view

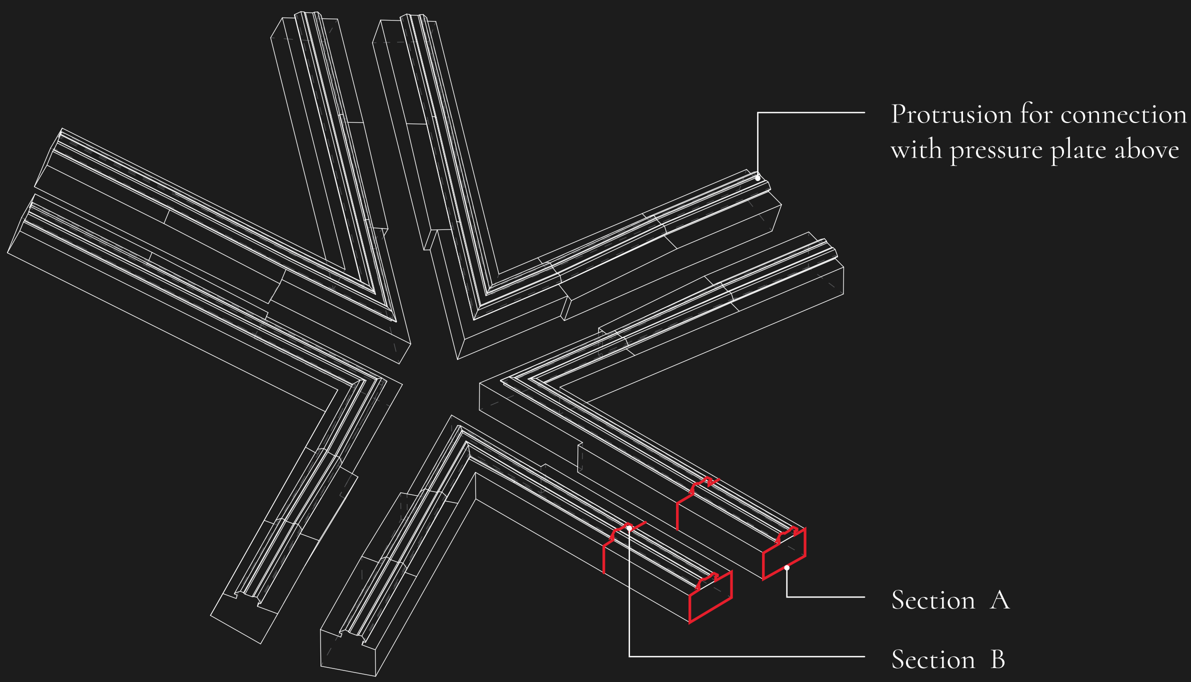


Figure 4.4.23: Exterior Gasket (schematic) Isometric

Nodable Pressure Plate

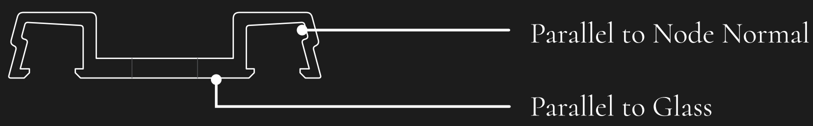
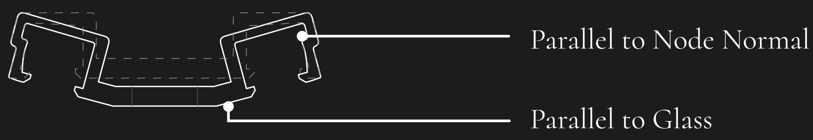


Figure 4.4.24: Section A:



Fugure 4.4.25: Section B: Concave Glazing

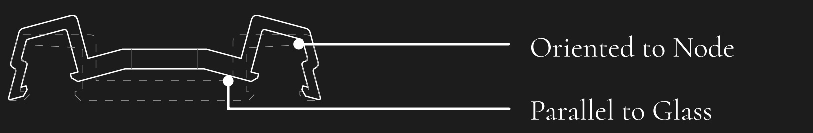
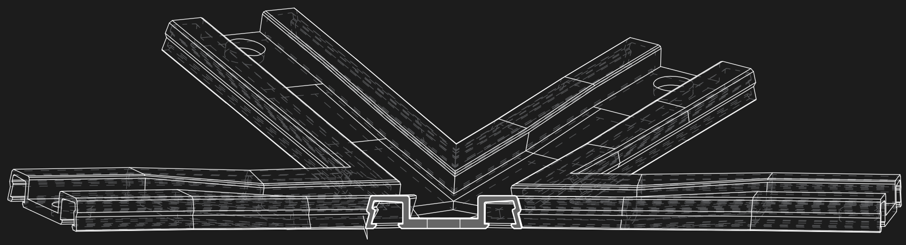
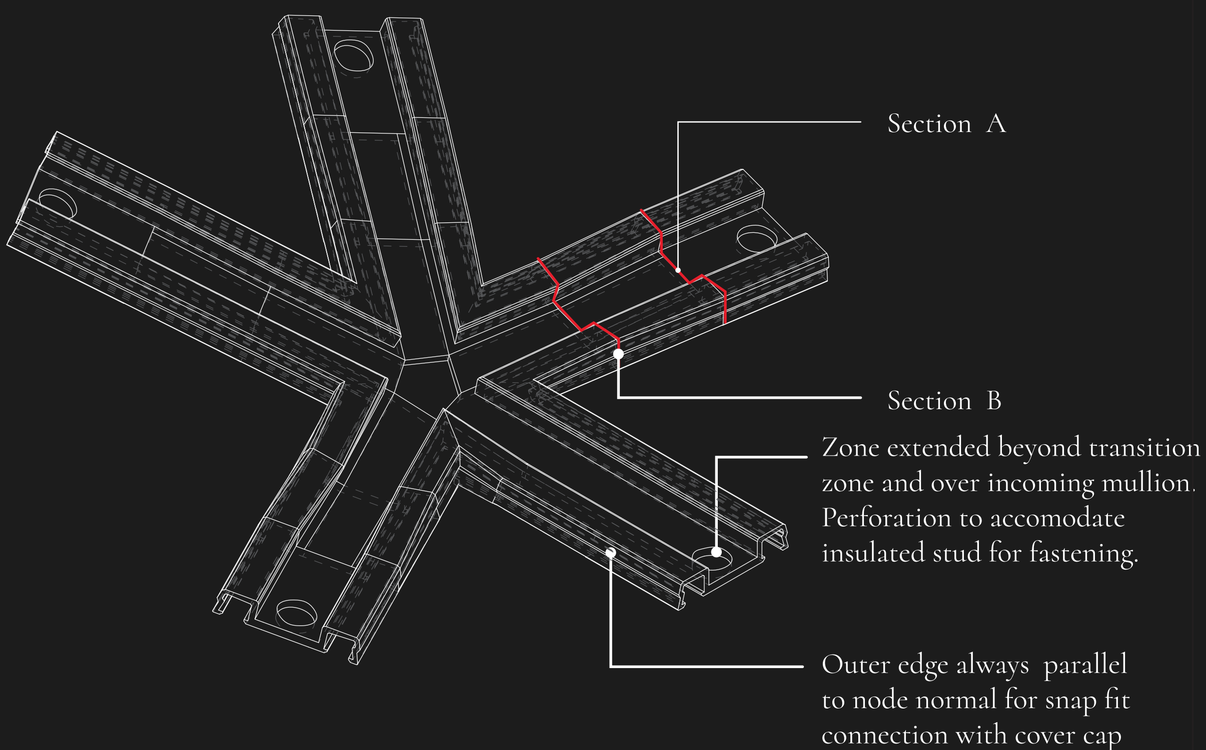


Figure 4.4.26: Section B: Concex Glazing



Fugyre 4.4.27: Pressure Plate Front view



Fugure 4.4.28: Pressure Plate Isometric

Nodable Cover Cap

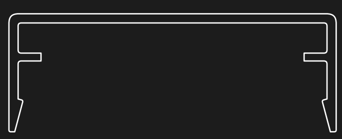


Figure 4.4.29: Section A

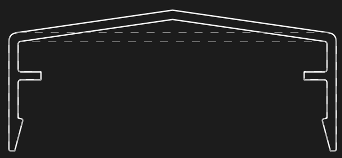


Figure 4.4.30: Section B

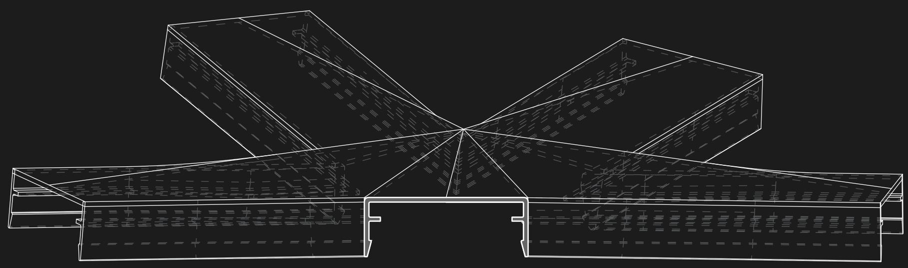


Figure 4.4.31: Cover Cap Front view

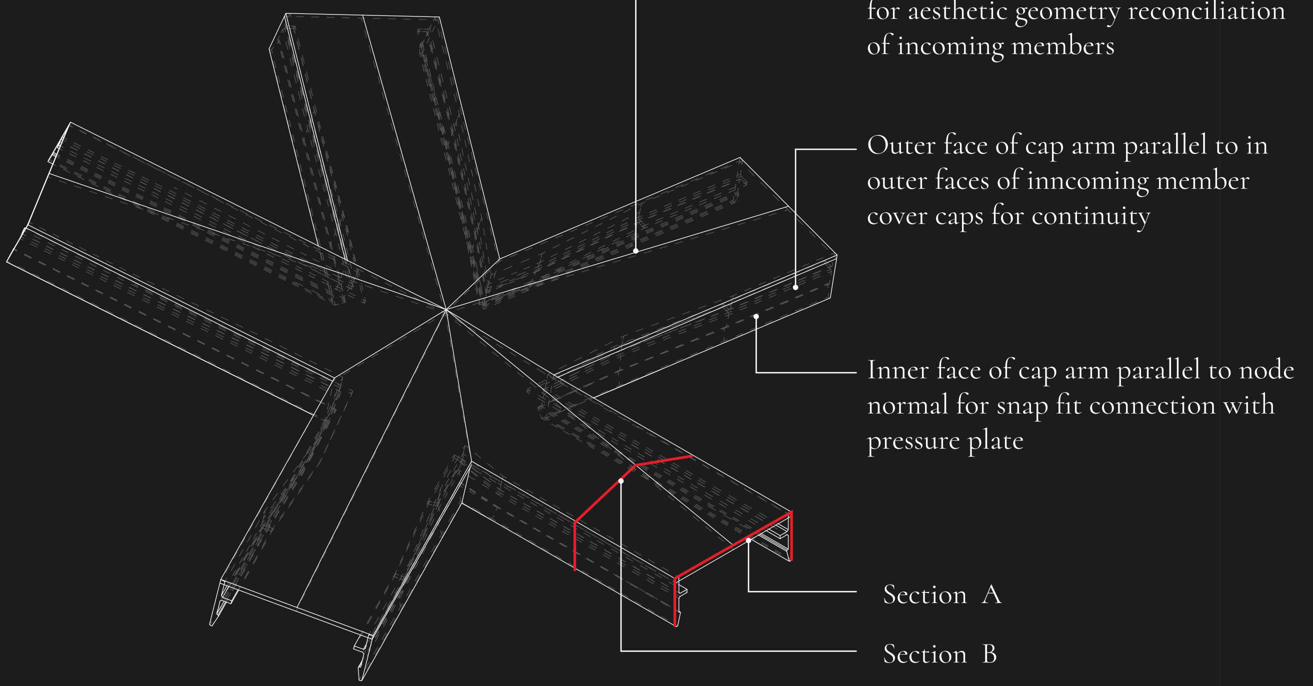


Figure 4.4.32: Cover Cap Isometric

Typical Mullion Members

(Complete Fabrication Details)

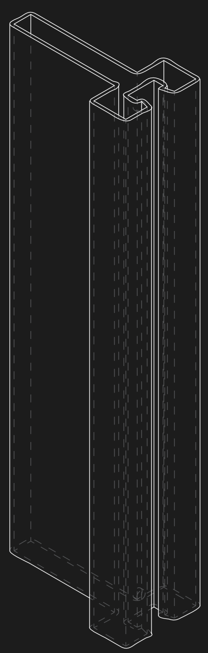


Figure 4.4.33:
Typical Linea Mullion
Isometric View

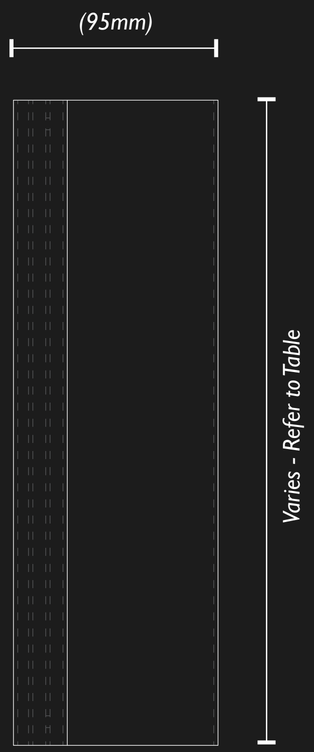


Figure 4.4.34:
Typical Linea Mullion
Side View

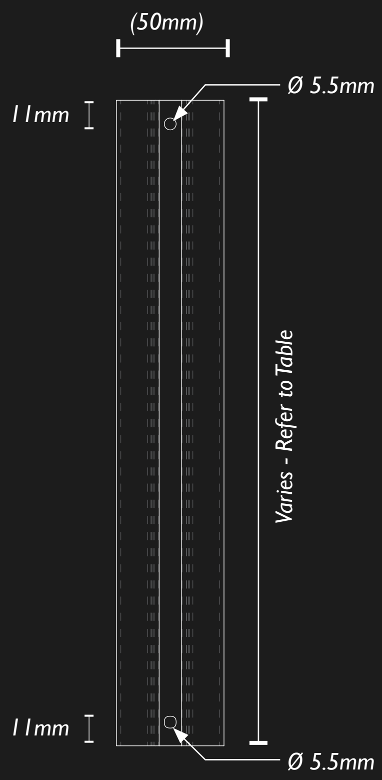


Figure 4.4.35:
Typical Linea Mullion
Front View

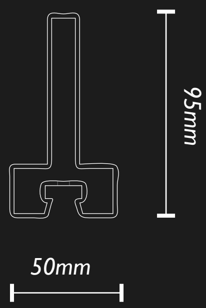


Figure 4.4.36:
Typical Linea Mullion
Section

VISS Profile ID	Member ID	Quantity	Length [mm]
76,115	Linea_0	1	2567
76,115	Linea_1	1	3557
76,115	Linea_2	1	2355
76,115	Linea_3	1	3239
76,115	Linea_4	1	1927
76,115	Linea_5	1	1930
76,115	Linea_6	1	1720
76,115	Linea_7	1	1469
76,115	Linea_8	1	2082
76,115	Linea_9	1	2057
76,115	Linea_10	1	1510
76,115	Linea_11	1	2139
76,115	Linea_12	1	1787
76,115	Linea_13	1	2026
76,115	Linea_14	1	2586
76,115	Linea_15	1	2352
76,115	Linea_16	1	2250
76,115	Linea_17	1	2047
76,115	Linea_18	1	2958
76,115	Linea_19	1	2016
76,115	Linea_20	1	2255
76,115	Linea_21	1	2166
76,115	Linea_22	1	2461
76,115	Linea_23	1	2432
76,115	Linea_24	1	2432
76,115	Linea_25	1	2520
76,115	Linea_26	1	1362
76,115	Linea_27	1	2415
76,115	Linea_28	1	1806
76,115	Linea_29	1	1749
76,115	Linea_30	1	1442
76,115	Linea_31	1	2279
76,115	Linea_32	1	4115
76,115	Linea_33	1	2216
76,115	Linea_34	1	1678
76,115	Linea_35	1	1800
76,115	Linea_36	1	2433
76,115	Linea_37	1	3392
76,115	Linea_38	1	1892
76,115	Linea_39	1	1991
76,115	Linea_40	1	1371
76,115	Linea_41	1	1273
76,115	Linea_42	1	1867
76,115	Linea_43	1	2605
76,115	Linea_44	1	1611
76,115	Linea_45	1	1664
76,115	Linea_46	1	2279

Figure 4.4.37: Fabrication ticket details for hypothetical wall assembly

4.5
Connection

The connection for the system is based on the Push-in connecting spigot, which is the simplest existing attachment mechanism for the VISS system. The main advantage of the system is that it requires little to no preparation of the transom after it is cut to length. The main disadvantages of the systems are that the structural connection is inferior to a welded connection, and that the system is not suitable for installation between two fixed points, which is a necessary feature for a free-form facade.

The design for the nodable connection uses available features of additive manufacturing to overcome the shortcomings of the attachment system. The push in connecting spigots are redesigned as deployable pieces integrated into the node to allow mullion profiles to be fitted between two fixed points. The connectors are embedded within the transition zone of the node arm during printing. The transition zone for this reason does not alter the inner shape of the profile in section. The connection is printed on two rail extrusions built into the shell of the node. The connector slides along the rails to engage with the sections.

The connector is engaged by sliding a key (Figure 2.5.4) into the top slot built into the node and through the connection piece. The key allows enough leverage behind the connector to slide it along the rail, emerging from the front face of the node and sliding into the incoming mullion. The circular extrusions provide the main structural support for the connection. The rectangular extrusion slides under the groover of the mullion, and the perforation line up to allow the connector to be secured using expansion bolts for hollow steel sections (Hansen, 2014) (Figure 2.5.2)

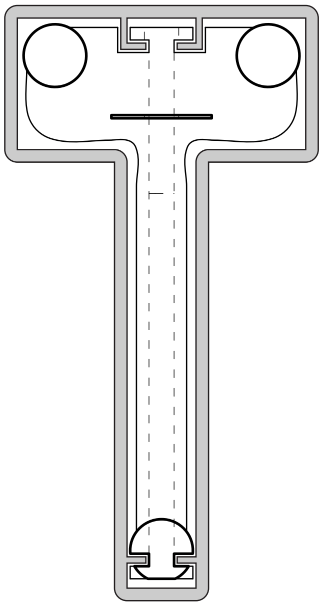


Figure 4.5.1: Section Through Node and Connector

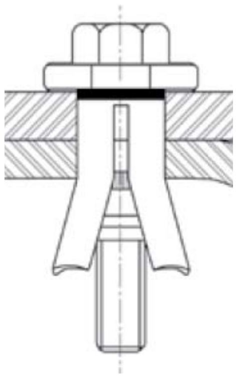


Figure 4.5.2: Expansion Bolt
Source: Hansen, 2014

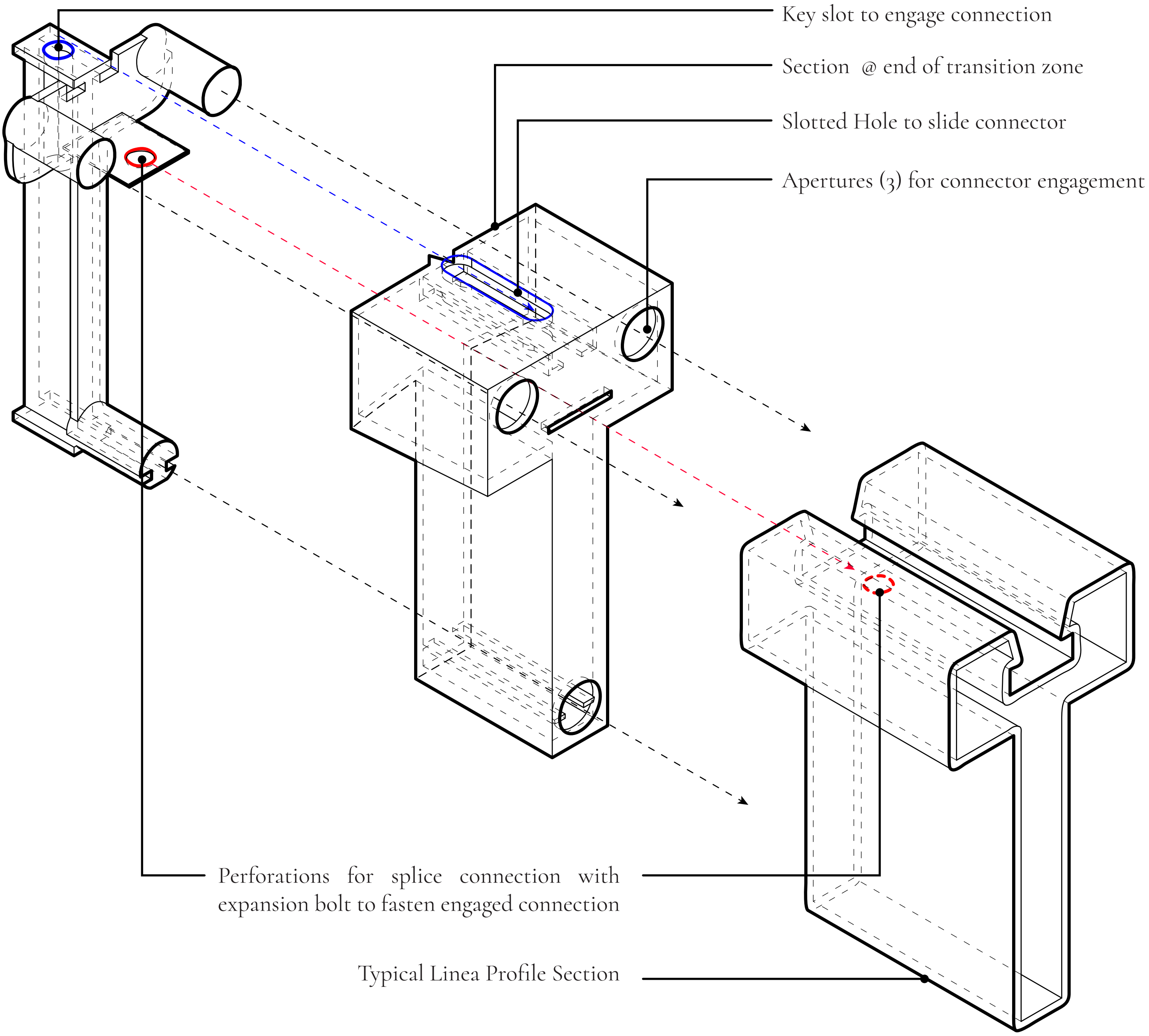
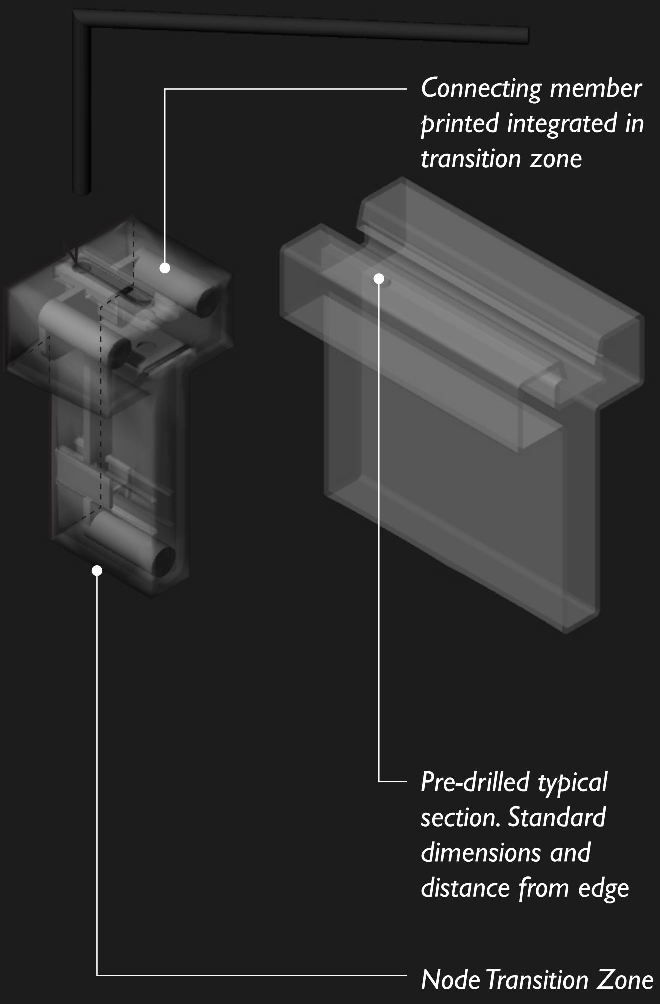


Figure 4.5.3: Connection Exploded Isometric

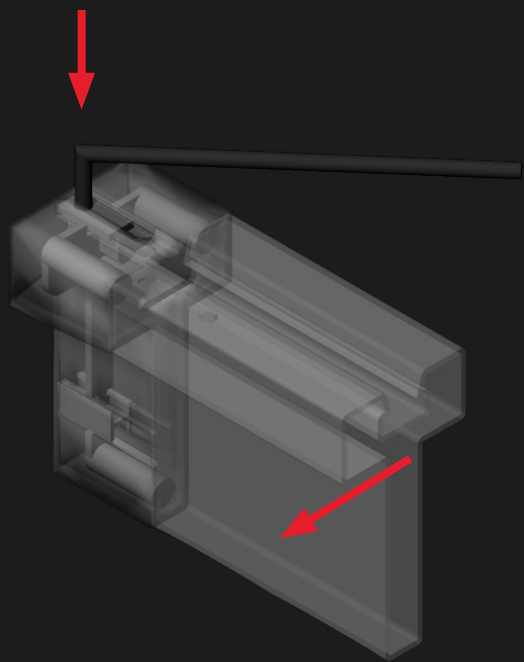
1

Prepare standard sections.



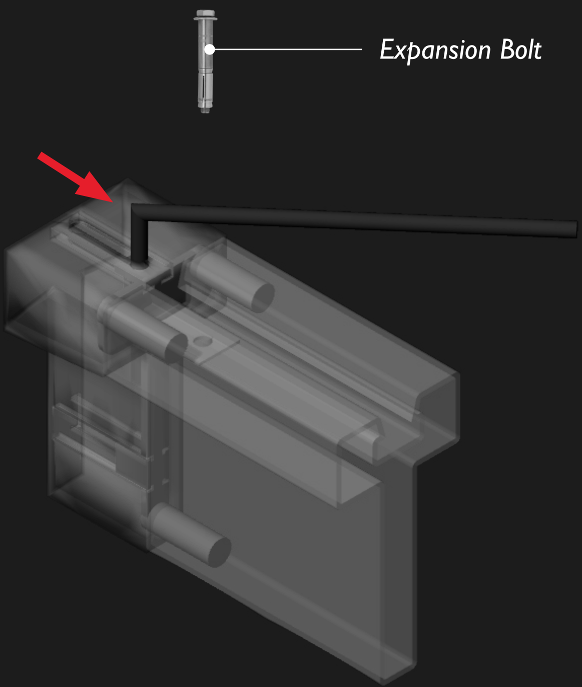
2

Insert section between fixed points.
Engage connection key.



3

Engage connection element.



4

Secure splice connection using expanding bolt.

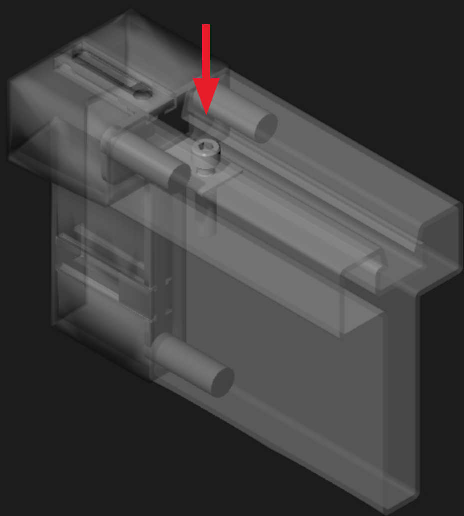


FIgure 4.5.4: Connection Sequence

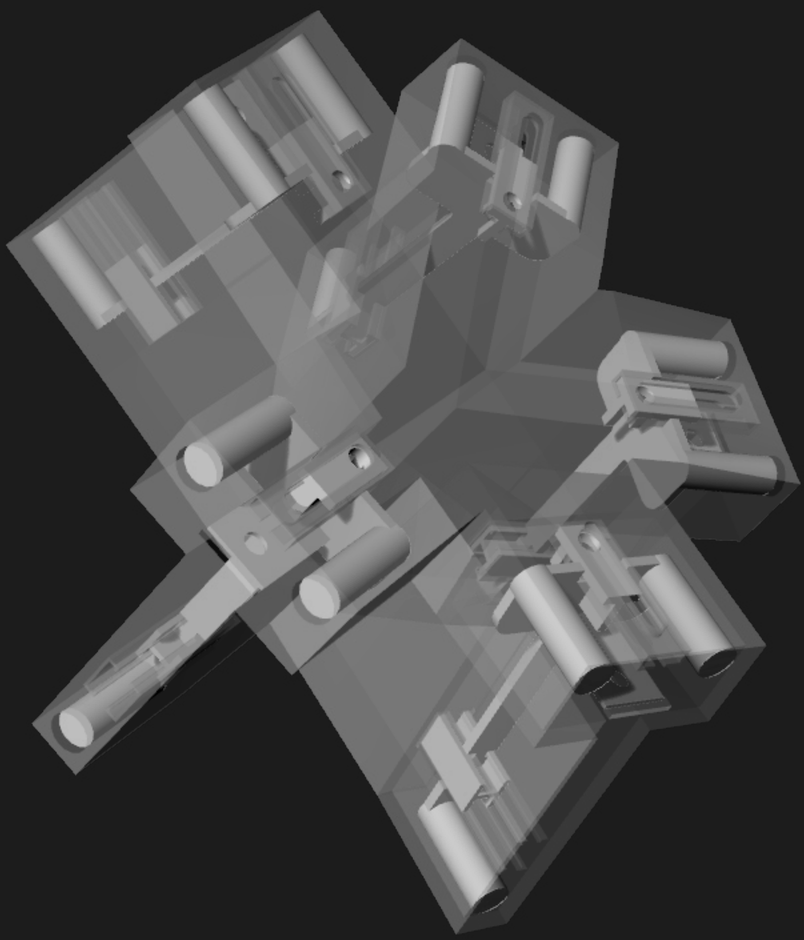


Figure 4.5.5: Attachment Configuration - During Printing

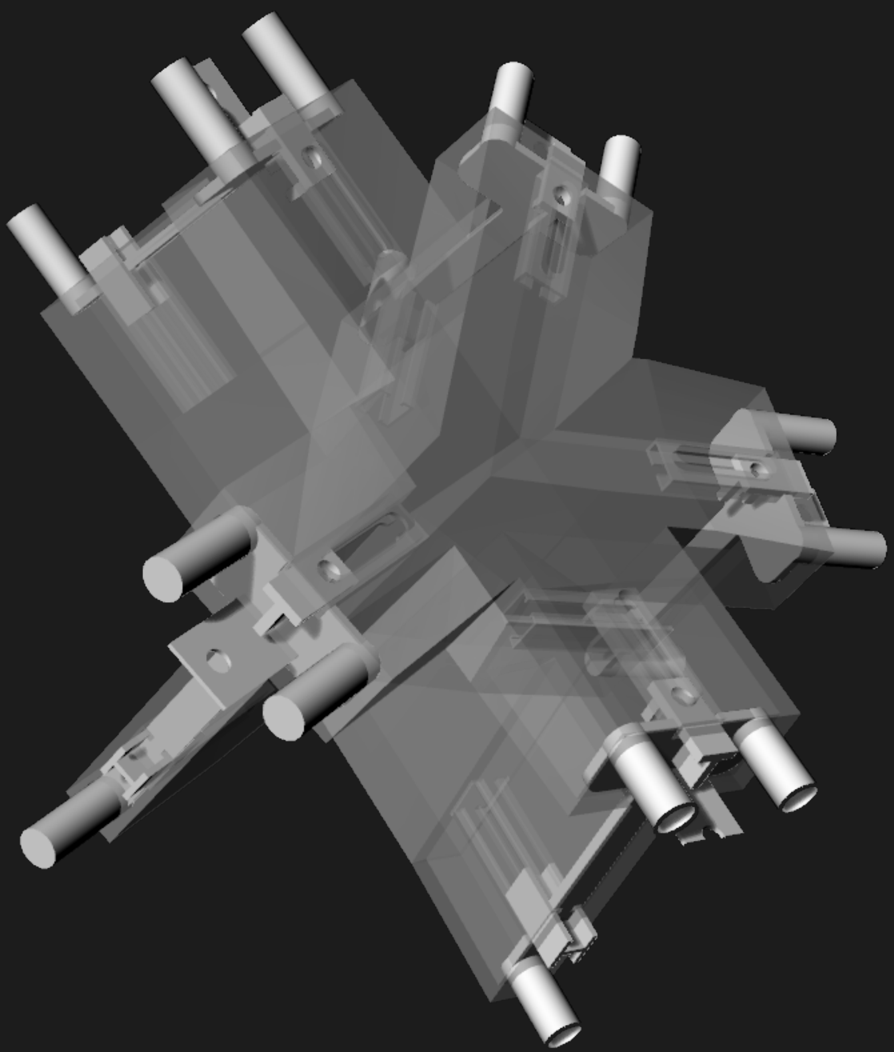


Figure 4.5.6: Attachment Configuration - Deployed

4.6
Assembly

The assembly sequence of the 3d printed node is similar to that of the typical system. the overall order of the assembly is the same, and provisions are made for connection to the node elements to their respective typical elements.

1

In the first step of the installation the main structure for the facade is assembled followed the steps outlined in the previous section - engaging the node with the typical sections and securing the connection with bolts. This enables the following steps to take place as outlined in the assembly instructions (Included in Appendix), which includes the installation of the insulating studs and the glazing supports.

2

Once the insulating studs and the glazing supports are in place along the typical profiles, the interior gasket for the node can be placed. The interior gasket has a flat extension that extends over the typical sections and enables attachment to the outer insulating studs.

3

Once in place, the typical interior gaskets can be installed, lapping over the extension, and using butyl sealing strips for a watertight attachment. The nature of the AM interior gasket eliminates the need for the notching of the gaskets, which is explained in detail in Appendix docuents.

4

Once the Gaskets are in place the glazing can be placed and secure in the typical fashion with the use of short segments of pressure plates.

5

The center pressure plate can be installed. The pressure plate extends beyond the transition zone of the node in order to be fastened to the typical mullion via the insulating studs.

6 7 8

The fastening of the remaining pressure plates completes the installation of the load bearing elements of the assembly. To complete the assembly, the center and typical cover caps can be spanned onto the pressure plates in the typical fashion.

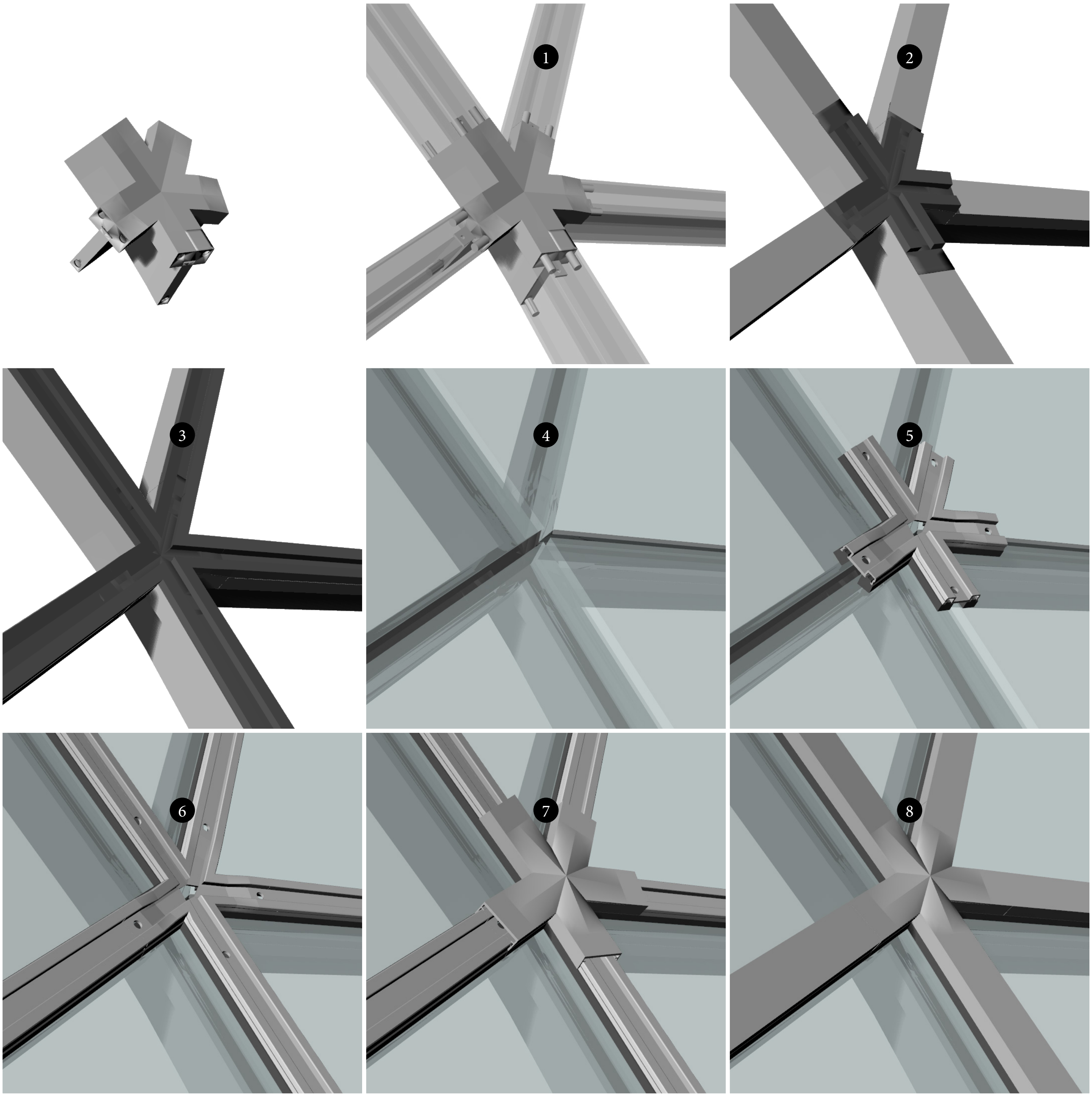


Figure 4.6.1: Assembly Sequence for Nodable Component with Typical VISS System Components

05
nodable+

The base nodable design makes use of computational design and additive manufacturing to create free-form node from a parametric logic of geometric relationships. This node improves on the shortcomings of traditional free-form facade nodes by having more accurate and more deliberate geometric transition, reconciling various incoming planes and volumes to a single center, and greatly improving the ease of assembly of curtain wall mullions, especially between two fixed points. While this system already provides great advantages to the design and assembly, the digital framework that is inherent to this workflow enables an ever greater potential for this product.

Structural optimization presents an opportunity to take the base design a step further, by taking advantage of additive manufacturing to enhance the performance of the node and reduce its material use in addition so solving its geometric challenges. Three options for structural optimization, namely free-size optimization, topological optimization and an internal lattice, are considered. The former presents an opportunity to reduce material use and create a node with a unique aesthetic, creating apertures in the node that locally increases the transparency of the system. The nature of the solution provides material only where necessary for custom loading conditions. The latter also potentially enables reduced material use but provides a more monolithic solution that maintains the bounding volume of the node. This solution could present the opportunity to improve sightliness by modifying variable parameters of built into the node definition, such as the depth of the flange.

While both solutions are equally valid and worth exploring, topological optimization is the selected option. Topological analysis requires the definition of design-space, in which he material will be reduced to the minimum volume, and nondesign-space, which is not optimized. The design-space for the node consists of the narrow interior flange (Figure 5.0.1), whose purpose is uniquely structural (the front portion of the section profile affects the control layer performance of the enclosure). While the flange in the transition zone has to house the connectors during printing, the section highlighted in yellow has no function outside of structural stiffening.

This process uses as a foundation the research by Bayu Prayudhi, which optimizes a given facade structure on both general ad specific loading patterns, in order to provide a proof of concept for the integration of topological optimization as an added feature to the Nodable system.

NOTE: All graphics in sections 5.0 through 5.4 have been produced by Author unless otherwise noted

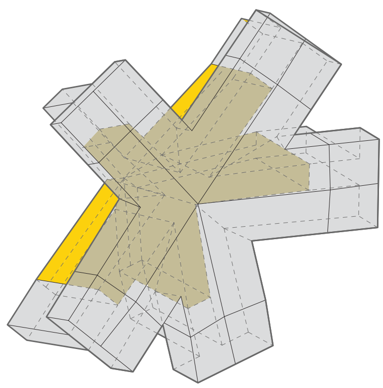


Figure 5.0.1: Design Space for Future Optimization

5.1
Structural Optimization Matrix

Structural Optimization is a means to take advantage of the geometrical capacities of additive manufacturing technology to improve the structural performance of the node in a way that traditional manufacturing is unable to achieve, or unable to do so in a time and cost efficient way. The structural optimization can be done in a number of ways. This study considered three options in particular: A combination of size and shape optimization in which seciton thickness can be optimized and internal reinforcements added as necesary; Topological Optimization based on results of structural analysis; and a lattice optimization in which a lattice is generated inside the structure, potentially enabling an overall shape optimization.

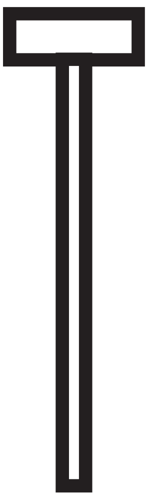
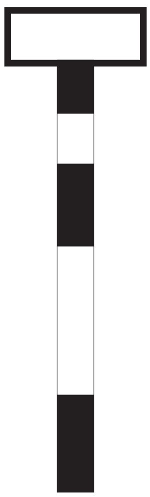
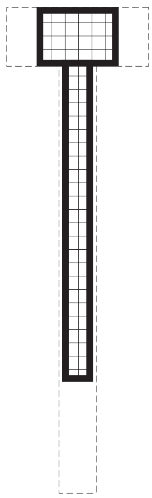
Structural Optimization		
Optimized wall thickness and internal reinforcements if/as necessary to fulfill minimum required structural function + Simplest Geometric solution & Modeling - Does not take full advantage of AM technology - Uses potential supplementary steel due to lack of optimization	**Optimize Topology (TopOpt) portion of Node** + Optimized Structural Behavior + Clear AM Aesthetic + Can easily make use of additional subtractive post-processing - Complex Engineering	**Fill with lattice structure, enable scaling down of section to reduce visual intrusion. Can be interior or exposed lattice.** + Optimized Structural Behavior + Optimized Sight-lines - Complex Engineering - Requires AM technology that does not require additional subtractive post-processing (particularly inside)
	 Selected Option	

Figure 5.1.1: Shape Optimization Matrix

5.2
Advanced Design Digital Workflow

The added process for the implementation of topological optimization can be integrated into the existing digital workflow with the addition of the advanced design and additional post-processing. In the advanced digital workflow, the structural model built with grasshopper and karamba, is exported into Autodesk Robot using the Geometry Gym plug-in. The structural data from this analysis is used in combination with the geometrical data generated in Rhino/Grasshopper and Solidworks. The optimized mesh is rebuilt in Rhino using Tsplines, and is brought into Autodesk Fusion 360 and combined with the rest of the component geometry, then exported to .stl similarly to the base design workflow. Figure 5.2.1 illustrates the entire digital workflow for the advanced design. Highlighted objects represent steps that are added to the base design workflow.

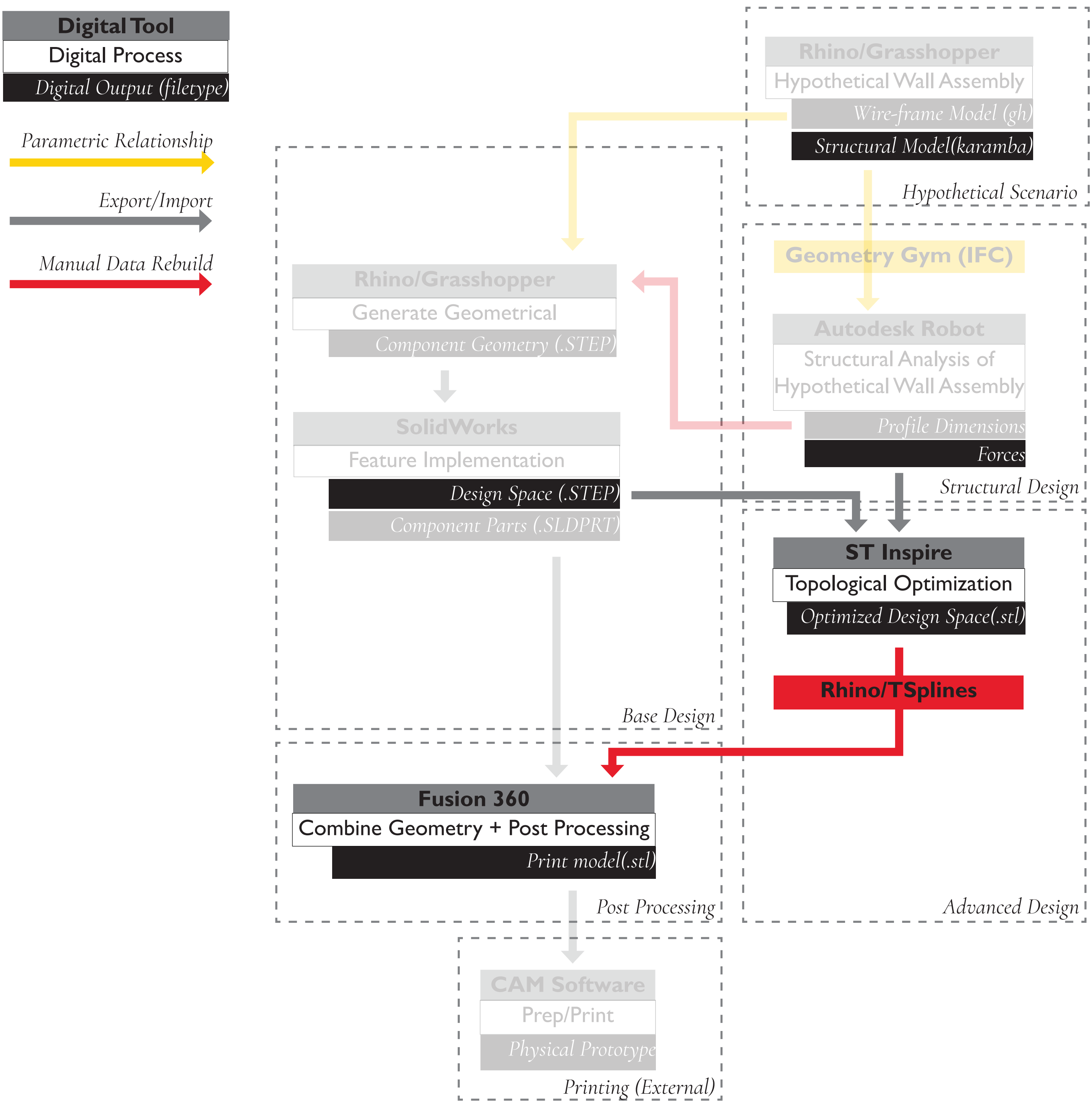


Figure 5.2.1: Nodable Advanced Design Digital Workflow

5.3
Optimization Process

While structural behaviour is not the primary focus of this research, it is necessarily an subject of interest in the development of a free-form node, and a potential avenue for taking advatantage of additive manufacturing. The following excercise in topological optimization is a proof of concept for the integration of the optimization process in the digital workflow and the final product. As such, the focus of this excercise is centered on the generation of a schematic output that can be integrated into the final design and post-processing.

Initial Analysis

The hypothetical wall assembly, which is a doubly curved faceted surface with freeform U, V, and W angles, is used as the base for the excercise. The model is assembled in grasshopper using the karamba plug-in, and exported to Robot using geometry gym. This process enables in particular the seamless transition of the location and orientation of the structural sections, which would be a painstaking endeavour to model manually directly in the Robot workspace. Loads, support conditions, and safety factors are applied. The robot workspace provides a more intuitive environment for the iterative process of generating a balanced analysis model, in comparison to Karamba. The members are initially modeled as pin connections, fixed in translations and fixed in rotation only around the local x axis. The members are iteratively released in translation at one end along X axis to relieve large normal force in a number of members. Once a satisfactory model is achieved, local X, Y and Z forces for each incoming member are extracted for the optimization model.

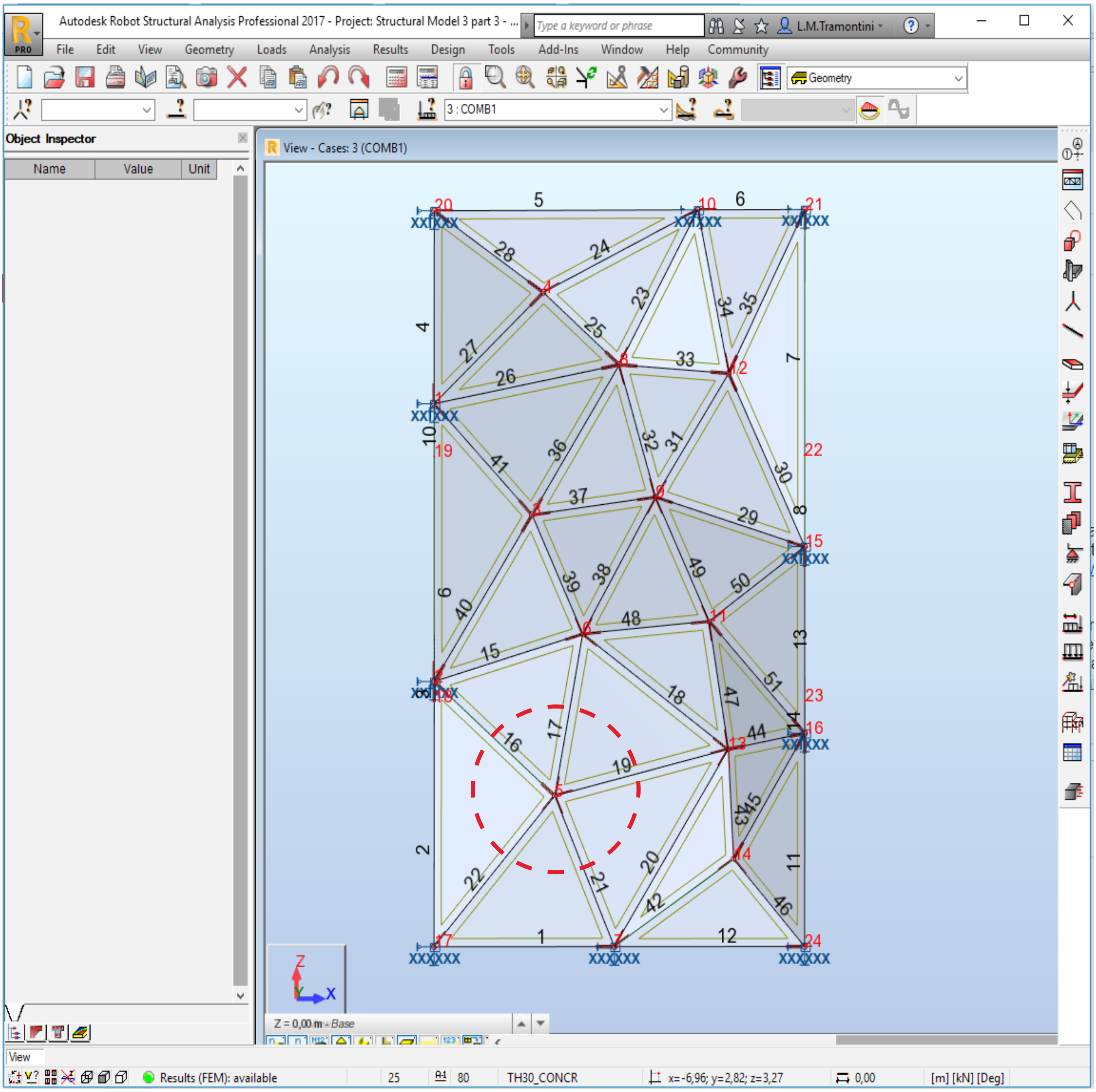


Figure 5.3.1: hypothetical wall assembly - Autodesk Robot Model Screesnshot

Optimization Analysis

There are a number of tools available for topological optimization. In research on topology optimization for free-form building envelope design with additive manufacturing by Bayu Pradhi, the author defines a comprehensive workflow based in altair hyperworks that takes into account both the specific behaviour of individual nodes under specific loading conditions, as well as a more general loading conditions to accomodate other possible loading patterns. While the application of this process would indeed provide a good solution for this application, the process is rather complex and time-intensive.

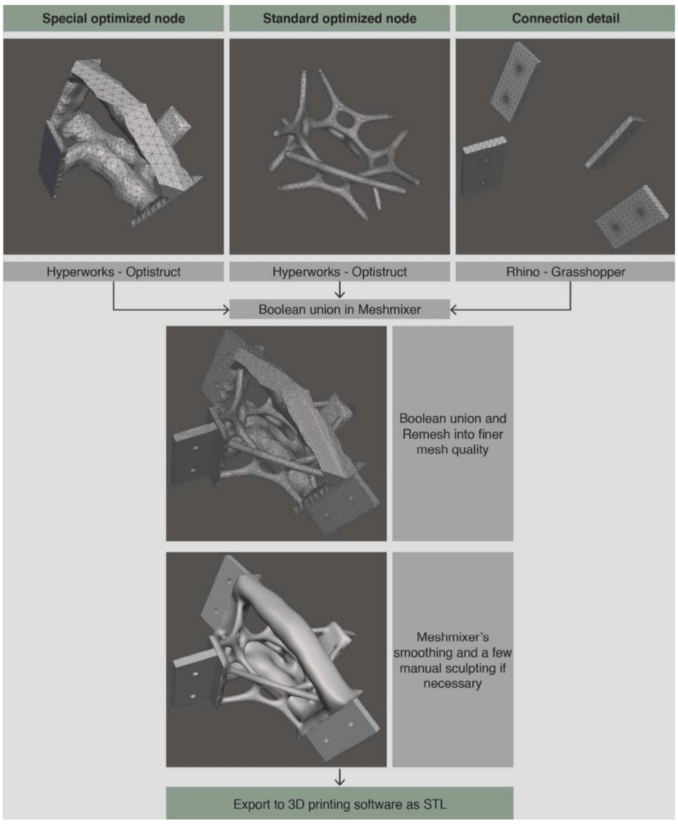


Figure 5.3.2: Process for topology optimization for free-form building envelope design with additive manufacturing
Source: Prayudhi (2016)

The process for the purposes of this research are greatly simplified in order to achieve a hypothetical optimized mesh for proof of concept. In this analysis, Solidthinking Inspire, a user-friendly Generative Design/Topology Optimization software for design engineers that enables them to create and investigate structurally efficient concepts quickly and easily, (Altair) is used as the optimization tool.

The input for the optimization process consists of the geometry output from rhino/grasshopper and solidworks, and the numerical output from Robot for the applied forces to the node. The node is imported in two pieces as STEP files, the first piece, the design space is brought in directly from Rhino, and the non-design space is brought in from SolidWorks. The force output from Robot is re-oriented from the local axis of each mullion to world coordinates and applied to the model in SolidThinking Inspire. Pinned supports are applied to the cylindrical facdes of each of the apertures in the face of the node, and released in rotation and translation along the axis of the surface. a minimum thickness of thickness of 5mm is applied as well as a safety factor.

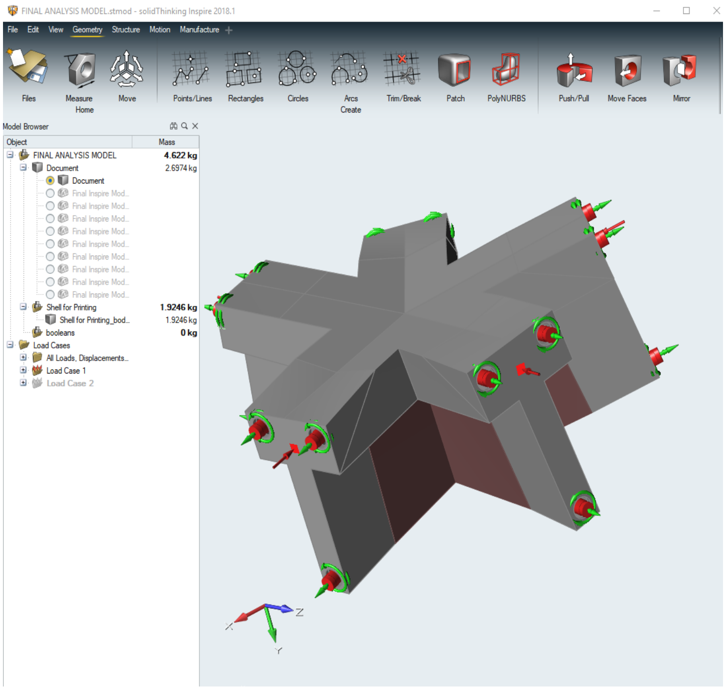


Figure 5.3.3: Altair Optistruct Hypermesh Optimization Setup

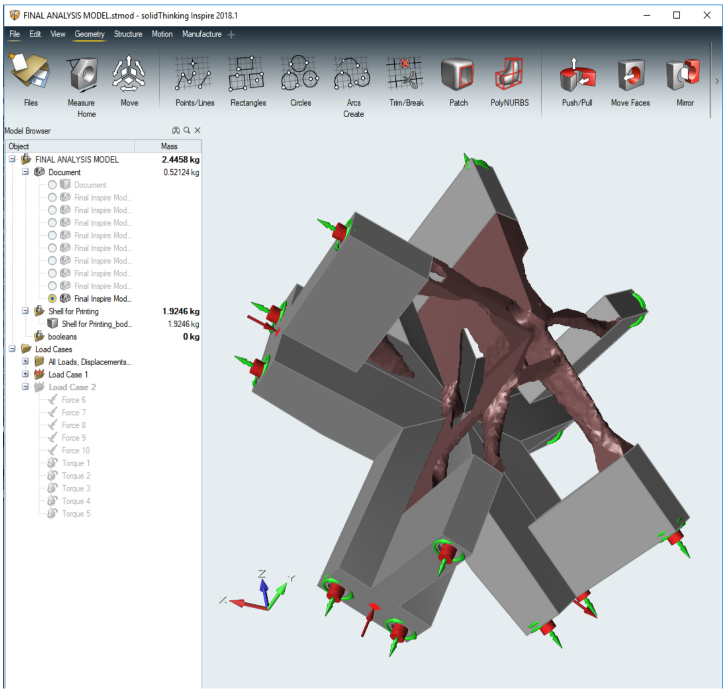


Figure 5.3.4: Altair Optistruct Hypermesh Optimized Mesh

5.4
Post Processing

The result of the optimization process in SolidThinking inspire is a rather rough and jagged mesh. The mesh is imported into Rhino, and TSplines, a Rhino plug in that excels at generating free-form geometry, is used to manually replicate the mesh exported from SolidThinking Inspire. Figures 5.4.1 and 5.4.2 Illustrates the comparison of the original mesh exported from SOlidThinking Inspire to the model replicated manually using TSplines. A number of other alternatives were explored, including several mesh editors both in the Rhino/Grasshopper platform, as well as third party tools such as MeshMixer, however none of these tools generated a sufficiently smooth mesh for the desired level of finish of the node. That being said, the replication of the mesh with T-Splines was a tedious manual effort. Further research into other options for post-processing a mesh to generate a smoothe printable peace would be of great benefit fo rthe workflow.

The generation of the optimized portion of the node is the last modelling endeavour in the process. Once generated, the model is ready to be assembled and exported for printing. Autodesk Fusion 360 is used as the final platform before exporting. The tool allows you to import individual components, carry out boolean operations, perform modelling changes, and verify the model using measuring and clash detection tools. Once ready, the components are exported as stl files for printing. The Make 3D Print function in Fusion 360 enables the option to print directly to a printer-specific application, either mesh mixer, Print Studio or PreForm, or as a generic stl file with custom, or preset export settings. Each component for this prototype were exported to stl using the high refinement settings.

Figure 5.4.1: Original SolidThinking Inspire Mesh Export

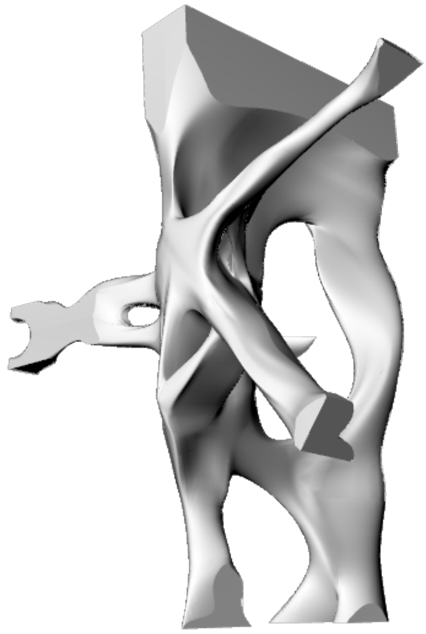


Figure 5.4.2: Regenerated Optimized Geometry using TSplines

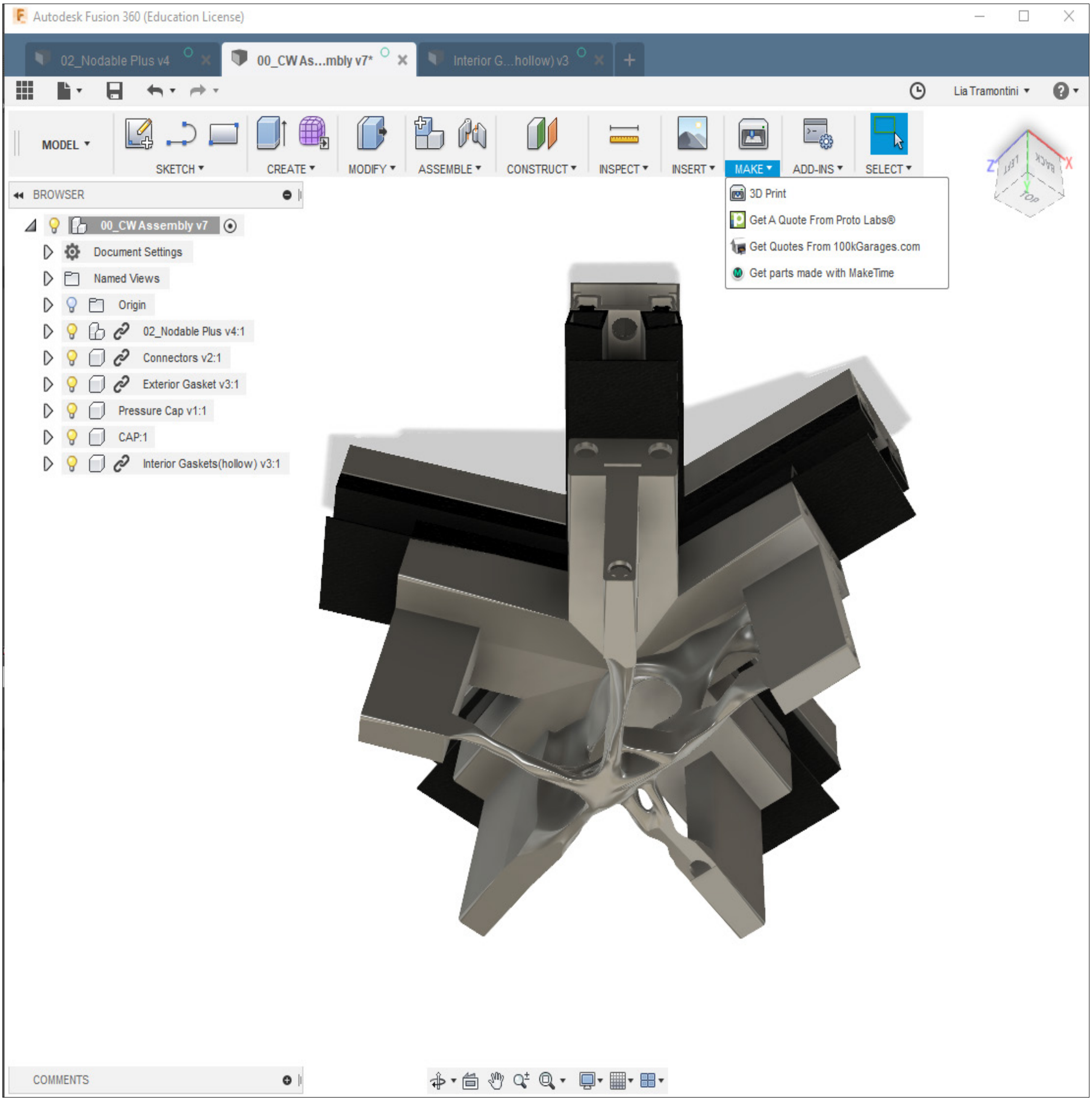
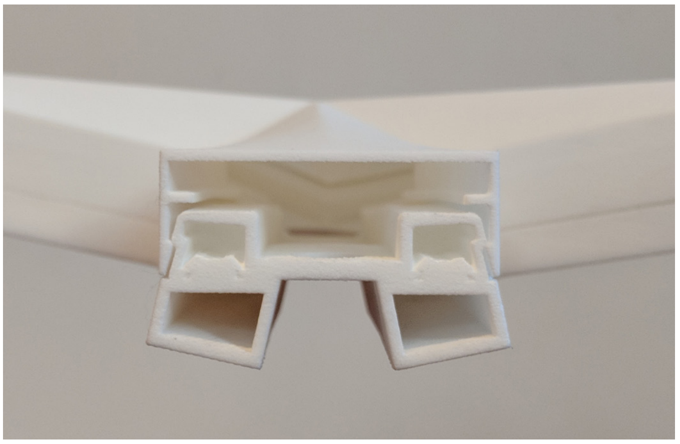


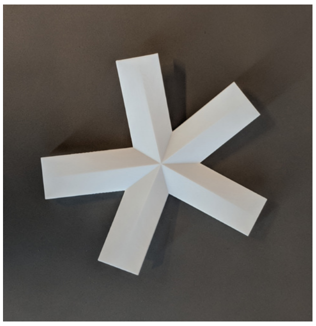
Figure 5.4.3: Fusion 360 Imported components for export to stl

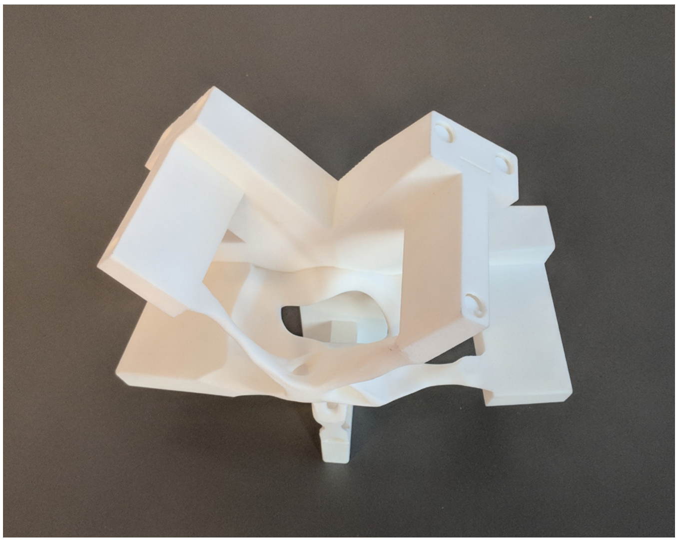
06
Prototype

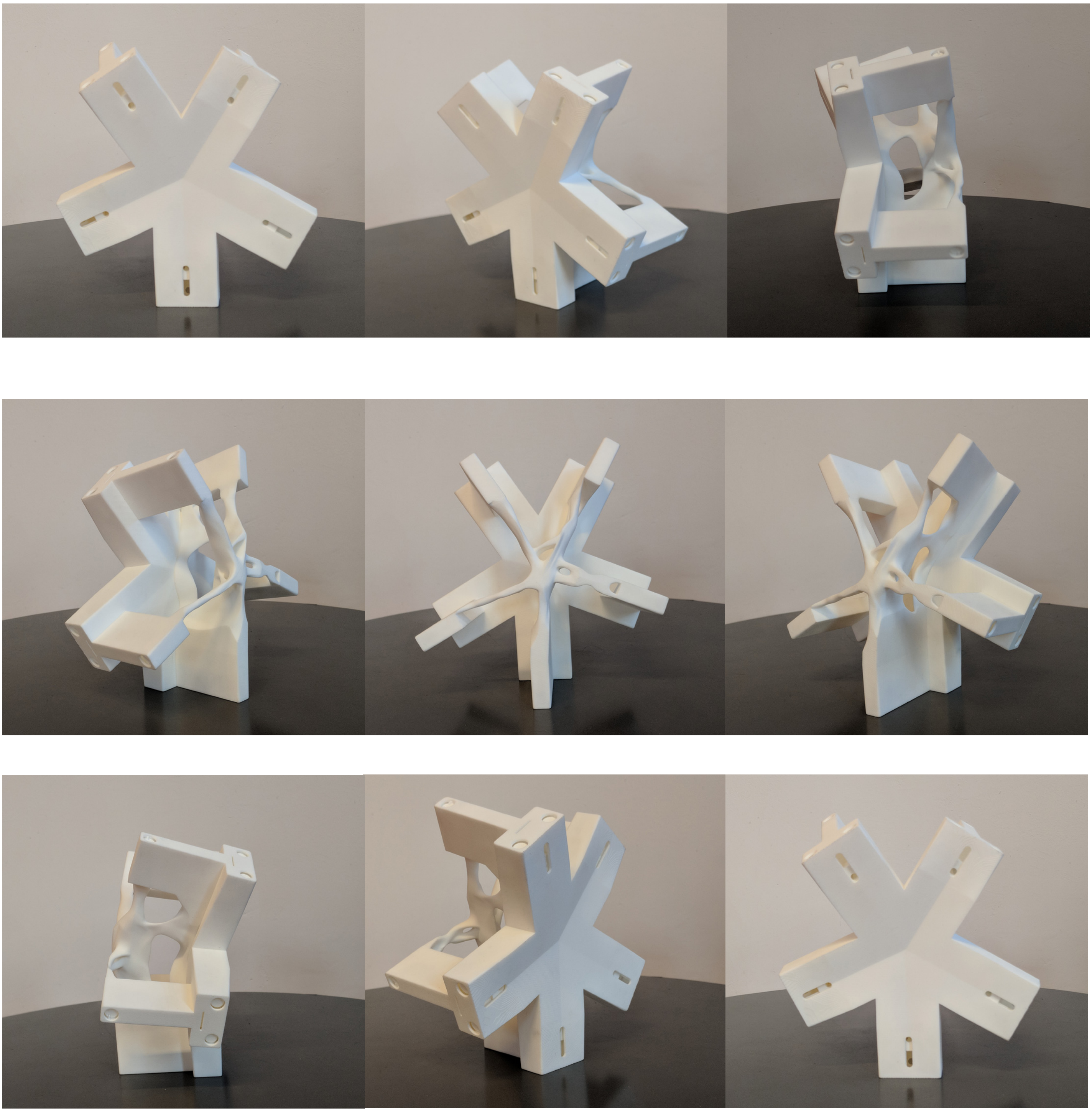
The prototype is printed in nylon plastic using selective laser sintering technology. This material choice offers a relatively cost-effective material choice for a prototype whose purpose is to test and demonstrate the geometrical strategy and assembly mechanism of the system. SLS offers a comparable method of printing with similar advantages and challenges to DMLS, which would eventually be used to print the metal product. The print consists of four printing files: the main body with the integrated connecting parts, the interior gasket, the exterior gasket integrated with the pressure plate, and the cover cap. The prototype is configured for 8mm plexiglass “glazing”.

The node was selected from the hypothetical wall assembly. It features both convex and concave angles, as well as five incoming mullion members.









07
Conclusions and Discussion

Geometry & Performance

The proposed geometrical strategy provides a viable solution for addressing the challenges related to air/water/vapour/thermal control of the building envelope in freeform curtain walls. While freeform curtain walls have excellent performance and have a highly efficient fabrication and assembly when applied in orthogonal systems, freeform systems require much a more labor intensive process, and result in a less precise, less efficient, and less reliable system. The solution outlined in this report begins by clearly defining the relationship between input geometry and construction elements, and uses this relationship as a foundation to gradually transition elements of varying orientations into a single closed (watertight) element, whose outer faces reconcile into a single point. This method of treating the geometry provides a reasonable surface with minimal obstacles for the application of the control layer elements. The actual performance of this system has not been tested, due to the lack of time and resources for fabricating a large enough prototype for testing. This is a logical next step in the development of this product. In addition to improved performance, the design provides an aesthetically monolithic solution that is able to maintain machined quality aesthetic characteristics (planarity, profile section, etc) of the incoming mullions, all without highlighting or even exposing the connections mechanism. This is in contrast to the precedents studies in section 2.5 in which the solutions are either an extensive kit of parts with exposed bolts or welded connections. If desired, the application of topological optimization (nodable+ design) provides an opportunity to implement a unique, intelligent aesthetic, integrated into the eometry of the node, maintaining its monolithic shell.

Assembly

The assembly of the system s a significant and improvement on traditionally manufactured freeform facade application. The proposed design provides opportunity to reduce the number of steps necessary to assemble the system, simplifies the steps involved, and improves the capabilities of the connection. In, for example, a welded freeform system, the fabrication process requires extremely careful and measured cutting of members to come together in such a way that when welded together, the pieces, which are coming in at different angles in elevation and in cross section, form a fully closed (watertight) connection. While some strategies (for example, the schuco parametric system) uses cylindrical sections to simplify this challenge, cross sections such as rectangles or "T" profiles can prove nearly impossible to reconcile. This challenge applies not only to the main structural element of the assembly, but in all of its cross-section components. In the case of the gaskets in particular, precise cutting and joining is crucial to the control performance of the curtain wall, and its durability and corrosion resistance. For the cover cap, frabrication relies on careful craftsmanship to avoid an eyesore at the finish layer of the assembly. In the proposed design, geometrical complexity is dealth with in the interior portion of the node, where AM enables crosss sectional changes and freeform geometry that can gradually reconcile the geometry into a watertight component. This takes away completely the need to cut and join at custom angles, requiring only 90 degree cuts, making the fabrication of adjoining elements as simple, effective, and reliable for a freeform curtain wall as it is for an orthogonal application. The system also enables the ability to connect a mullion between two fixed ends , and this without adding to the complexity of the fabrication of the mullion. All of the complexity of the conection is contained within the node itself, which is additively manufactured, while the mullions only need to be cut at 90 degree angles (and in come cases perforated). This is a further improvement on the current available options which require, for a mullion to be installed between two fixed ends, to be fitted with additional pieces welded on to enable push on connection.

The assembly sequence for the node reflects the assembly of the VISS precedent. the AM node removes a number of the more time-consuming steps of the assembly, revolving particularly around the installation of the structure and the gaskets. As the main focus of this research was centered on the geometric resolution of the system, it should be noted that a number of the components outlined in the assembly require additional design attention. For example, in the current design, the vertical gaskets and horizontal gaskets are the same, meaning that the horizontal gaskets do not currently provide openings for drainage, nor are they equipped with a flap that laps over the top edge of the glazing. Further development of the node would resume on the geometrical logic developped for other components, and continue the development of a fully functional system.

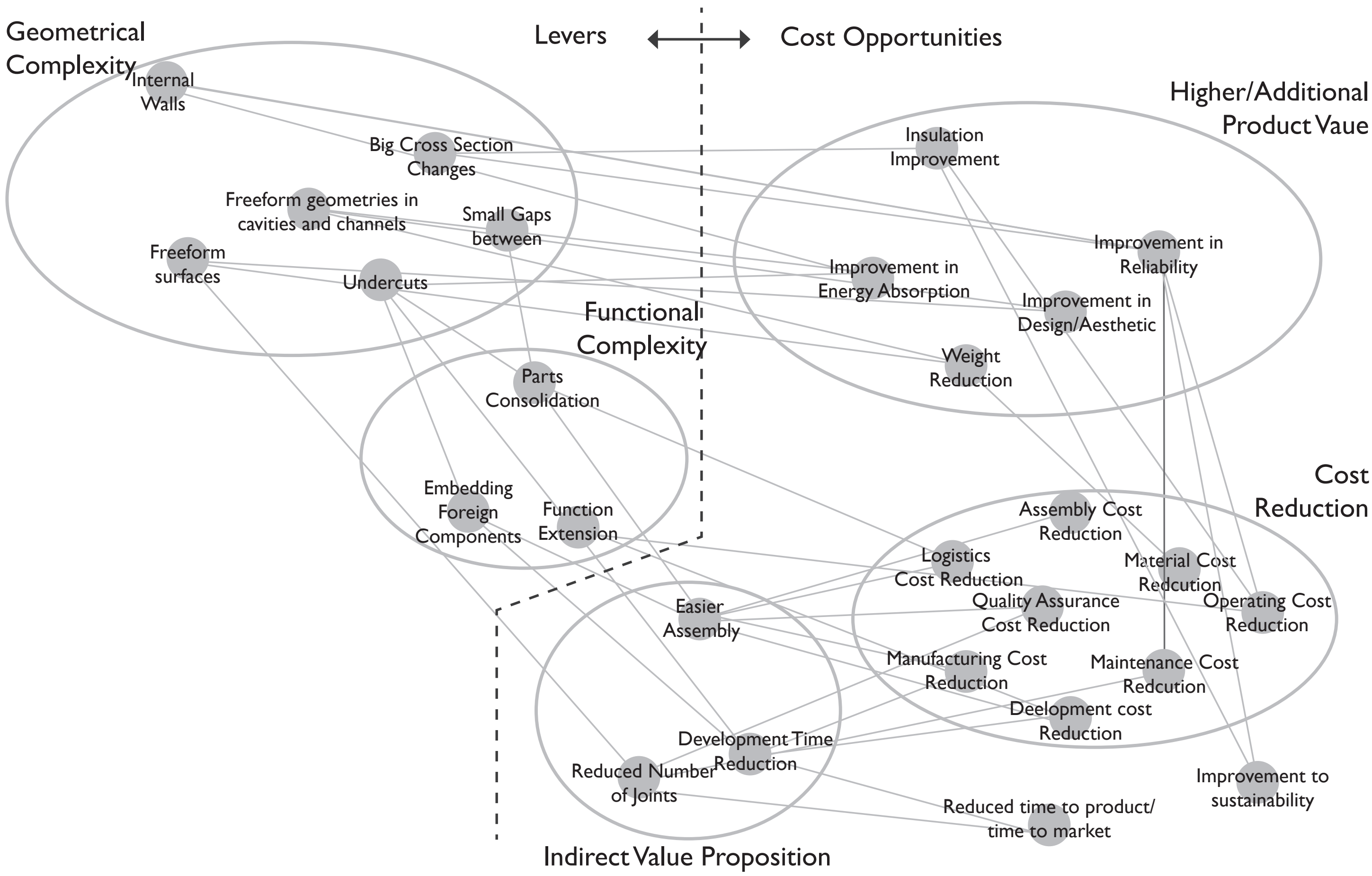
Use of Additive Manufacturing

Ths use of additive manufacturing is paramount in the design and development of the nodable system as it has enabled a design freedom from which typical curtainwalls systems cannot benefit due to maufacturing limitations. In particular, the node benefits from two types of additive manufacturing freedom: geometrical freedom and functional freedom.

The geometrical freedom of additive manufacturing enables the monolithic generation of irregular and organic shapes embodied mostly in the cross-sectional change towards the center of the node, and the organic form of the optimized node. The node is the result of its input reference geometry, and as such, as elements in the section get further away from the reference geometry, the more that they require geometric modification in order to be able to reconcile at a point. The use of additive manufacturing enables the generation of a section profile that is gradually and selectively modified - skewed and twisted - along its section profile in order to maintain its performative functions and general aesthetic quality. This subtle and gradual modification to the cross section of the incoming elements is not conomically feasible with traditional manufacturing - with which the only available options are to limit the geometrical flexibility of design to fall within a threshold in which the geometrical disparities between incoming elements are more manageable, or to create a node that does not closely reflect the geometry of the incoming profile. The use of AM also enables the enhancement of the cross section with cross-sectional functional features, namely the rails that enable the movement and engagement of the connectors. Features such as rails, raceways, and internal reinforcements are features that aren't typically used in steel systems due to economical manufacturing limitations of steel sections. These features, however are common in aluminium systems, which, although have their own merit, lack many of the qualities of steel systems desired in certain applications. The use of additive manufacturing lifts the limitations on the manufacturing of steel elements, and enables them to take advantage of equivalent and enhanced functional features. In addition, in combination with other digital tools, additive manufacturing allows the implementation of additional features that are almost inconceivable with traditional manufacturing methods - steel or other - which enabled the system to take advantage of topological optimization.

The use of additive manufacturing and its ability to print nested movable parts is what ultimately enables the node to facilitate installation of mullions between two fixed ends, as the connector is fully embedded inside the node during printing and prior to engagement. This facilitates the assembly of the entire system, and avoids the design of a complex node that require a complex assembly of its own, like many of the examples shown in section 2.5.

Ultimately, as eluded to in Figure 3.2.1, geometrical and functional complexity are additive manufacturing design strategies that a number of cost savings and value opportunities for the product. The following is a modified version of Figure 3.2.1 with only the levers and design cost-opportunities related to this design. Here we see the relationships between the specific uses of geometrical and functional complexity and they repercussions on the cost and value of the end product.



At the same time, the design has a number of parameters affected by the use of 3d pinting, according to principles of DFAM. The shell of the main node, for example, requires a number of holes in it to allow removing powder from the print after printing. This requirement is integrated with the slots at the top of the node that allow the installer to engage the connectors. Moving parts are separated by 0.5mm per specific printing tolerances. Many of the characteristics of the node, also are designed to minimize the amount of printing necessary. For example, the definition resolves the minimum reach of each arm of the node based on the intersecting volumes of the incoming sections. This means that each arm has a different length, which on one hand reduces the necessary printing, but on the other creates joints that are all at different distances from the center of the node which aesthetically perhaps is no ideal. The alternative, however, is that each incoming arm has the same distance, which would necessarily be the longest of all of the minimum distances of each arm in a given node, which not only increases the printing prices (which is significantly more per unit weight than mass manufactured sections) but could potentially result in prints that exceed the limitations of the printing bed.

Reflection on Digital Workflow

The digital workflow presents an opportunity to facilitate, automate, and communicate between a number of the steps involved in the design (architectural and engineering) and processing of the node. The workflow developped for this project was a combination of tools selected for their abilities and compatibility. The workflow selected is by no means the only available option, or likely even the most optimal one. It is impossible given the number of tools available for all of the different functions to explore them all in the time frame for this research. That being said, the workflow selected ultimately did enable the design of a free-form node, albeit not flawlessly, and it is a worthwhile endeavour to outline the strenghts and weaknesses of the workflow as well as a number of unexpected obstables discovered during the course of the research.

The use of grasshopper as the main platform for the main geometry of the node proved a useful and effective solution. The user-friendly parametric capabilities of the tool enable the exploration of a number of design options, and the integration of a variety of flexible design parameters. This is particulary relevant in this application because the systems come as a kit of parts with a number of available options - profiles and dimensions, etc. - that can be used in different combinations within the system. grsashopper enables the relatively simple substitution of one element in the kit of parts for another. It is lso a valuable tool, since its platform is compatible with a number of other tools that are useful in the development of the node. If not directly, then often through third party tools, such as geometry gym, which enabled the seamless translation of a grasshopper/karamba stick-frame model into Autodesk Robot for analysis.

While the Rhino/grasshopper platform has extremely powerful capabilities, it is not without its own limitations. A significant example of this is the challenge of working with boolean operations in grasshopper which can often be a cumbersome and unpredictable endeavour. Boolean operations that would fail in the grasshopper space might succeed in the rhino space, or with the toggling of document unit tolerances. or for some unknown reason in only a fraction of equivalent applications. Another limitation of the tool proved to be the generation of a closed shell with an even thicknesss from a complex polysurface. There was apparently no tool available in grasshopper for effectively generating such geometry, and even in Rhino space, manual functions would more often than not fail to generate a solid object. A number of plug-ins were tried for both Breps and meshes and no satisfactory result was generated. This unexpected challenge resulted in the integration of Solidworks, a tool specifically for product development, into the digital workflow. Conveniently, another advatnage of rhino is the large library of filetypes that it is capble of importing and exporting. The node was exported in pieces as in STEP file format (Standard for the Exchange of Product model data) and brought into solidworks. In solidworks, the main node geometry was easily turned into a shell with an even thickness , and boolean operations were performed without glitch, combining the rail geometry and the main node shell, and subtracting volumes for the apertures in the outer faces of the node for the connector, creating a single closed volume. While the addition of solidworks into the digital workflow enabled rather easily overcoming the shortcomings of working with Rhino/Grasshopper, it also means a hard stop in the workflow - meaning that once the node enters solidworks, any work that is done on the node will have to be re-done for each individul node, and each time a node is regenerated for any reason. While this is rather undesirable, the workflow only requires solidworks at the very end of the geometry generating process, and once generated, the geometry does not need to go back into rhino/grasshopper for further development. In addition to this, Solidworks does have some parametric capability for its feature functions, meaning that for example the thickness of the shell or the radius of perforations can be altered parametrically in Solidworks.

Once the geoemtry is generated, it is brought into the optimization tool. A number of optimzation tools were looked at in terms of their ability to perform 3D topological optimization, ability to accurately represeesente different loading/support conditions, compatibility with Rhino/Grasshopper and quality of optimized result. Ultimately, Solidthinking Inspire was selected as an optimization tool that enabled a relatively quick and reliable optimization with a user-friendly inerface. Given that topological optimization was not the main focus of the research, the latter was a very desirable feature. This application, however, has no means of extracting parametric information from outside sources. This means that for each node, all of the optimization criteria has to be defined manually and individually. This required translating local X, Y and Z force data from Robot into equivalent forces oriented to world coordintes and entering that information manually for each node face in SolidThinking Inspire. The optimization process for the node, relative to other steps in the development of the node, is one of two significant bottlenecks in the overall process. In terms of data management, the tools could benefit greatly from development that allow them to collect information direclty from other tools such as picking up force vectors from excel data, or third party tools that can translate the information for them, creating a more seamless transition between base design and optimized design.

The optimized geometry generated is a jagged mesh that requires significant smoothing to produce a quality print with a smooth finish (optimization is a careful balance between mesh resolution and running time). Further research would be very helpful in identifying and evaluating tools that are able to smooth an optimized mesh, maintaining the hard oundaries of the design space and maintaining the structural integrity of the component. Mesh relaxing tools, which are sometimes used for this purpose, have a tendency to thin out element sections at their critical points. Manually regenerating the geometry as was done in this workflow is a painstaking endeavour that can potentially be replaced with the right digital tool.

Next Steps

The current design as outlined in this report provides good first step in evaluating a range of possibilities for a potential solution to the challenge of free-form curtain walls. That being said, due to the limited time and resources for this research, there are a number of potential next steps for the further development of this product to explore before it is ready for industry.

► Critical review of application of AM. This research was an excercise in exploring a range of possibilities that AM could provide for free-form curtain walls. While consideration was given throughout the design to create an economical solution, all of the components within the design were developped to be entirely additively manufactured. As a next step, it would be beneficial to re-approach the design identifying where perhaps AM is superfluous or another solution is more sensible.

► Further development of assembly elements. The current soution for pressure plates and in particular the interior and exterior gasket focuses on the orientation of the main features of the components and their relation to ther other components in the assembly, the result of this is a schematic solution that does not fully address the function of the component, of drainage in particular, in all of its complexity. Further development of the gasket, either the continued development of the printed gasket, or the adpatation of the system for compatibility with the current gaskets, is necessary. In addition, further consideration could be given to components that have not been considered in node design specifically, for example, the glazing supports. The further development of these elements could benefit from asking questions such as: Does this element work as required in a free-form application? Does the function of this element change in a free-form application? Can this element benefit from additive manufacturing?

► Structural Analysis. The structural role of the curtainwall node, although it was not a main focus in this particular study, is an integral to development of a succesful solution. The proposed design takes structural behaviour into consideration, providing design features such as stiffening ribs, torsional resistance, and moment resistance particularly in the design of the connections, where they might be required. These features, however, are based purely on engineering judgement and not, as they should, on proper engineering analysis. Further development of this product would require adequate structural analysis to better understand the structural behaviour and overall performance of the node under potential loading conditions. This might result in the integration of internal reinforcements, or require the adjustment of design parameters such as cross sectional dimensionsor member sizes.

► Connection Development. The node connection as designed provides is fixed in rotation in local X axis and fixed in translation in local Y and Z axes (the connection provides some resistance to movement in local X axis with the splice connection between the mullion and rectangular extrusion of the mullion, however this resistance is limited). These conditions may not be sufficient for all applications. Further development of the connection would be necessary in order to provide adequate moment resistance in all directions when necessary.

► **Fabrication and testing of assembly.** While the result of this research provides clear improvements on traditionally manufactured alternatives in terms of geometry resolution and assembly, the actual performance of the system in terms of its air/water/vapour/thermal control performance has not been verified. The design would benefit from a scale mock-up for testing per ASTM standards in order to provide a clear picture as to whether of not the geometrical solution is successful in adhering to the performance standards of an assembly.

► **Refined Parametric Defintion**. The generation of the main geometrical solution defined by the grasshopper definition has the potential to be the foundation of a standalone tool for the generation of freeform curtainwall nodes. This definition could take as an input the wireframe geometry of a given curtain wall and export the node ready for engineering and fabrication. As is currently defined, the definition used for the purpose of generating the design presented in this research, was able to generate all of the main geometric components for each of the 20 nodes in the hypothetical wall assembly. However, slight modifications to the definition were necessary for a number of exceptional conditions, namely corner and edge nodes which are exceptions due to their relationship to the perimeter, and thus the asymetrical nature of the glazing for the perimeter elements. The definition requires fine tuning in areas to accomodate these exceptions seamlessly. In addition to this, the current definition requires a curve input as a means of selecting the profile from the available kit of parts for aplication in the definition. The curve is also slightly modified. In order for the definition to be a user friendly tool, it would be desirable that one could select the desired profile and that this selection be applied without the user needing in depth knowledge of the specific details of the definition. A necessary next step would be to package the entrire definition to require only a very simple set of inputs, namely a wireframe and profile selection, and that the core of the definition need not be touched.

► **Alternative Solutions**. As presented in this research, both the design and the digital workflow are only one of many solutions available in tackling the challenges for this type of application. As such, a next logical step in this research is the evaluation of alternative solutions for the design, as well as alternative tools in the digital workflow. While this research strove to look at a breadth of solutions throughout its course, the further investigation of other possible geometrical strategies, of other digital tools (particularly for analysis, optimization, and post-processing), and of other potential applications for optimized design, can potentially greatly improve the current design. This includes, for example the potential application of micro-scale features to the print, a feature which is not discussed at length in this report, but can potentially prove to be a functional asset in similar applications.

► **Complementary Research.** The continued development of this research will happen in parallel with a number of other studies and developments in industry that will help further this study. The continued development of additive manufacutirng technology will continue to make AM a more accessible, reliable and accepted method of fabrication. This includes in particular a focus on the structural behaviour of additively manufactured steel. The development of digital tools will improve the overall workflow of AM product development from conception through fabrication. This development includes amongst other things increased functionailty, improved interoperability and increased ability to represent mass-customized objects.

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