Parametric nodes from idea to realization

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Parametric nodes from idea to realization

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The radical change in architectural design transcends the individuality of design towards multi-various individuation. The immersion of parametric diagrams in the representation of architectural objects leads into a process that could be grasped and manipulated with a high degree of efficiency. Computational advanced design techniques are becoming necessary; therefore new techniques need to be implemented to work on retooling the traditional ways of manufacturing elements. To formulate the problem; Architects, façade engineers and manufacturers need a speculated new solutions and be their liaison for collaboration. Complex designs driven out of parametric potentials are characterized by the various angles and inclinations that form the mullions/sub-construction, which forms the desirable design. Accordingly, having a flexible connection that can provide a full range of proper angles, is requisite. Additive manufacturing also is known as 3D printing, is based on the theory that any object could be synthesized by breaking it down to multilayers that are needed to be laid at the top of each other to form the final object. Metal- Based additive manufacturing has significant growth in the last couple of years, based on the advantages that AM offers, which is producing complex 3D objects directed from CAD data without the need for that careful and detailed analysis that is needed by the other manufacturing processes. A unique collaboration between architects, façade engineers and manufacturers could be achieved by following a whole new aspect, which is how to move from Design to Production. The merge between design and manufacturing could revolutionize the building process of complex buildings. Moreover, the elimination of several constraints, which usually show up in the planning phases. Additively manufactured parts still need some verification to reach the level that the market and the user can accept and trust.

Keywords: Parametric, Nodes, Free-form, Additive manufacturing, Adaptive solutions

1 Introduction

New parametric design software tools nowadays, provide architects with unlimited possibilities to explore the unlimited potential of their creative vision. Accordingly, the design and engineering process of such sophisticated geometries became more complicated. This complexity placed façade planners and manufacturers in a challenging position as they are subjected to an exhaustive negotiation process with the architects in the process. The results of these negotiations are facing either rejection or reverting to individualization. Thus the final results can be costly most of the time. According to the evolvement of parametric software that the architects benefited from, façade planners and manufacturers need a similar mechanism that helps them to cope with these developments.

This paper is dedicated to the exploration of the design and engineering process of single-layered shells. Concerning economic aspects, single-layered shells consist of straight connecting bars, planar glass surfaces, and connecting nodes. Based on that description, the primary challenge is the design and engineering of the connected nodes. The main idea of industrial construction is the standardization of systems and products arbitrarily. This standardization aims to the increase of economic efficiency of the produced elements; through the developments of merely assembled and standard building parts. (Wachsmann 1959, Mengeringhausen 1966)

The trend in architectural design and façade technology is the increase in complexity. Baccarini stated in his review in the International Journal of Project Management " Construction projects are invariably complex and since World War II have become progressively more so" (Baccarini 1996). Complex projects demand special treatment, therefore that traditional project management found inadequate. Hough claimed, "complex projects demand an exceptional level of management, and that the application of conventional systems developed for ordinary projects have been found to be inappropriate for complex projects."(Morris and Hough 1987)

Project complexity has no precise definition. Different papers have discussed the definition of project complexity. It is concluded that project complexity defined by two dimensions, each of which has two sub-dimensions, Fig.01. (Williams 1999)

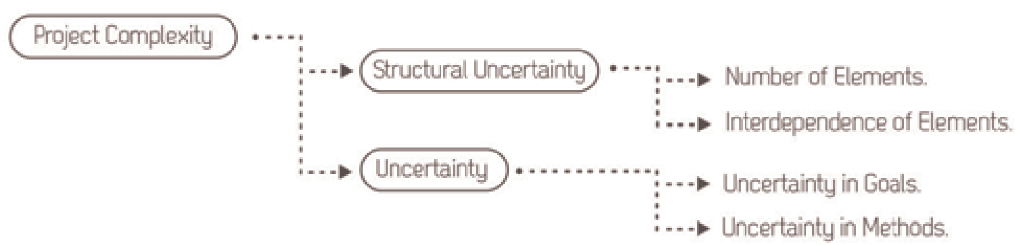

Fig. 1 The dimensions of Project complexity

The complexity of the requested geometry defines the structural uncertainty of the project. The increase in number and interdependency of the elements –e.g., connecting bars and surfaces- bring the planning process towards additional processes that cost time and money. The uncertainty in goals and methods comes through the post- processing of customized building parts, which requests additional testing and proofing.

Computational design has evolved immensely over the past few years and has been effectively used in designing complex geometries. However, constructing these geometries remains a challenge. Computational design has the potential to generate and optimize parts of complex geometries unrelated to its level of complexity.

Construction technologies do not develop as quickly or coordinated as Computational design tools. Accordingly, an adequate solution is needed to fill the gap between construction technologies and detailed geometric design, and to move forward towards a more homogenous design and engineering process.

2 Methodology

Free-form envelopes are transformed into free-form structural network. This structural network is made out of straight bars that have to be connected to one another through structurally designed and force-fitted connections. These connections are the node points, which form the required geometry and ease the orientation and the assembly of the connecting bars. The generation of these components can be parametrically designed using decent software, e.g. Rhinoceros© and grasshopper. This means that any geometry can be translated into its three main components – bars, surfaces, and nodes -. Complex geometries characterize by the various angles and inclinations, which the mullions/sub-construction have; to achieve the desired design. As a result, having a flexible connection that can provide a full range of proper angles is requested.

The idea of a universal node is still not been achieved, but many interested parties are working on the idea. Geometrical conditions and structure integrity define the design of nodes. Nodes connections are bolted, welded or specially fabricated. Each building regulation prefers a specific type of connection. The regularity of the structure determines the geometry of the nodes that determine the suitable fabrication technique, such as casting, extrusion, folding, special working and so forth. As well, the digital representation of the nodes in the parametric design phase, is sufficient for additive manufacturing techniques to manufacture the nodes.

Standardization, as defined in the business dictionary, means "Formulation, publication, and implementation of guidelines, rules, and specifications for common and repeated use, aimed at achieving the optimum degree of order or uniformity in a given context, disciplines, or field" (standardization 2018). Accordingly, designing a unique node connection – either part or process - that has the capability of being standardized and the flexibility to be applied to many geometries, will be the objective.

3 Design Development

3.1. Engineering Design

"Form follows function" has been the banner of designers since the Bauhaus (Lesko 2007). Based on that statement, the central concept is that function lead the form. Accordingly, the form position is lowered in the hierarchy of product design.

"Restated, it might read 'Form is the resolution of functions' where the function has two major components: (1) performance specification demands, including all user-friendly aspects, and (2) cost and manufacturability" (Lesko 2007)

The statement "Form is the resolution of functions" gives the form its dynamic and interactive properties, rather than "Form follows function", which showed the form as a passive party in the process. As a result, the designer has to observe manufacturability and its influence.

3.2. Parametric software programs

Drawings express architectural designs. The drawing medium is the primary constraint for drawing acts and organizing ideas, spaces, functions, and so forth. CAD software introduces a new definition for the drawing medium, which is the direct translation of drawings within the digital realm. Those drawings still just a digital representation (code) of the main ideas. The code creates geometry as a result, and this is direct Modeling, which presents the additive logic of traditional drawings.

Parametric as a term is related to various disciplines from mathematics to design. The term means using parameters to define range. Parametric in design refers to the use of parametric modeling, where parameters define the geometric rules and result in geometrical form. This form is controlled through algorithm, which could be changed through the defined parameters.

Algorithmic is a term that defined by the use of procedural techniques to solve design problems. An algorithm is a set of instructions that lead the design process. Codes instead of sketches and forms drive the design process here. These allow the usage of the power of computer programming languages, where the capacity of computers is operated as a search engine to allow difficult tasks to be performed in a small amount of time. Patrick Schumacher claims "the goal of parametric design is to establish a complex spatial order, using scripting to differentiate and correlate all elements and subsystems of design" (Schumacher 2009).

3.3. Traditional manufacturing processes

The commonly used materials in façade industry are steel, stainless steel, timber, PVC and aluminum. Each kind of material has its suitable manufacturing and handling techniques.

For example, when metal forming is discussed, casting processes – such as expendable molds, nonexpendable molds, die casting – are commonly used. Also, there are machining processes - such as drill, bore, mill, lathe, broach, and grinding (Lesko 2007).

In the façade industry, the used material defines the needed manufacturing technique and its process planning. In the case of complex projects, the traditional manufacturing techniques become inadequate. Accordingly searching for new or innovative solutions are required.

3.4. Additive manufacturing – 3D printing

Additive manufacturing is a process that is steered by the power of virtual 3D CAD data. This CAD data is transformed into layers, where the parts are made by adding these layers at the top of each other to form the final object (Gibson 2010).

The 3d printing process consists of several steps. These steps are as follows, Fig.02:

- Creating a digital model that defines the geometry's external surface.
- Exporting the targeted model in STL (stereolithography) format; this is suitable for nearly all AM technologies.
- Importing the STL file to the 3D printer's software - if provided- considering that each 3D printer may have its way to manipulate digital data and generate the appropriate G-code that is needed to run the 3D printer.
- The printing process starts after receiving the data generated by the step before.
- Creating the final model, which in some instances will require post-processing to finalize and prepare for end-use.

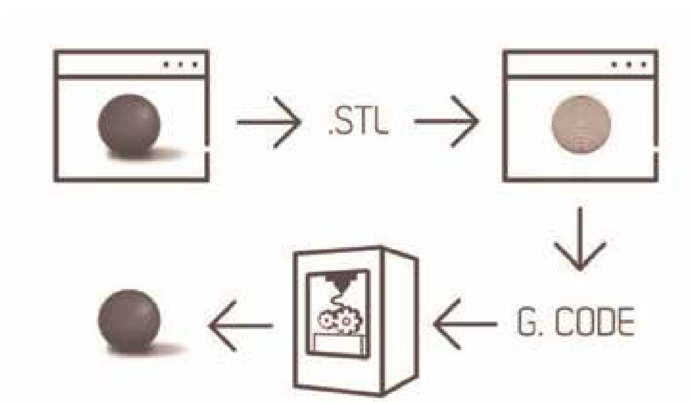

Fig. 2 3D printing steps

Additive manufacturing contains several techniques, which all used to help the generation of complex three- dimensional objects. Some of these techniques are extrusion and sintering-based

processes. Each technique has its limitations and capabilities, which should be accurately observed to accommodate the purpose and the usage of the generated object (Knaack 2016).

Selective Laser Sintering (SLS) and Selective Laser Melting (SLM) are the leading technologies that handle metals in the additive manufacturing method. Both technologies offer considerable possibilities to manufacture metal complex parts that can be beneficial for façade industry.

4 Solutions

The research generated Two generations of connecting elements, called N-AM 1st generation and N-AM 2nd generation. In the first generation, the idea was to define a solution that is represented as the connecting node with an irregular number of connecting bars. Rhinoceros© and grasshopper were used to parametrically define the location of the node inside the structure and accordingly define the exact profiles' lengths. The node was defined as a free hinge connection until it finds its perfect place related to the connecting profile and the whole form. The node design was intended to be traditionally manufactured, which affected the design because of its limitations but for economic reasons; traditional manufacturing techniques were adequate at that time of the research.

In the second generation, the idea is to define the connection node as a digital volume that is completely form related, which offers more freedom but as well as increase the range of node forms and its complexity. The size of the node can be defined based on its structural performance in the used case. The nodes can be directly manufactured by additive manufacturing machines, which help to reduce the process planning for the customized nodes.

4.1. N-AM 1st Generation

The spherical shape is round geometry in the three-dimensional space. Therefore, any object runs parallel to the surface of a sphere, could have complete freedom in the X, Y and Z planes. Moving from this point, having a ball connection embedded in a façade node connection, will be sufficient to provide enough freedom for the nodes' connecting arms. Based on the shape of the node, the inclination range could be defined. Several designs had been developed to achieve the maximum range of inclination that increases the range, where the node could be applied. As well the node should proof structural stability.

N-AM 01

Fig. 3 N-AM 01 Model

N-AM 01, Fig.03, consists of a rectangular plate that is connected to four spherical housings at each corner. The spherical housing contains a ball connected to insertion profile through metal stud. The arms of the node have 360° rotation around itself and ± 25° in every other direction.

N-AM 01 could be used as an attachment to the main structure. A bracket then needs to be used to accommodate the structure tolerances. It could be fixed as a free point, putting particular attention on the subjected loads and adopting its size accordingly.

N-AM 04

Fig. 4 N-AM 04 Model

N-AM 04, Fig,04, consists of a metal plate connected to four balls at each corner. The insertion profiles have to be integrated with the node that they contain the housing of the balls at the same time.

N-AM 04 prototype presented 360° rotation along the insertions' axes and ± 45° in every other plane. N-AM 05

Fig. 5 N-AM 05 Model

In N-AM 05, Fig.05, the distance between the center of the balls and the top side of the node, is decreased to lower the eccentricity. Accordingly, the location of the kern is raised, which gives more control over the connecting planes.

This modification allowed widening the range of freedom with about 10°.

The functionality had been checked by parametrically positioning the node in a façade element and observing different scenarios. These scenarios defined the maximum range for the nodes, Fig. 06-right. The design of the node considered traditional manufacturing techniques limitations. To study the structural performance of the nodes, a design for façade element was suggested and analyzed under the common load conditions that affect building envelopes, Fig. 06-left, such as own weight, wind load and so forth.

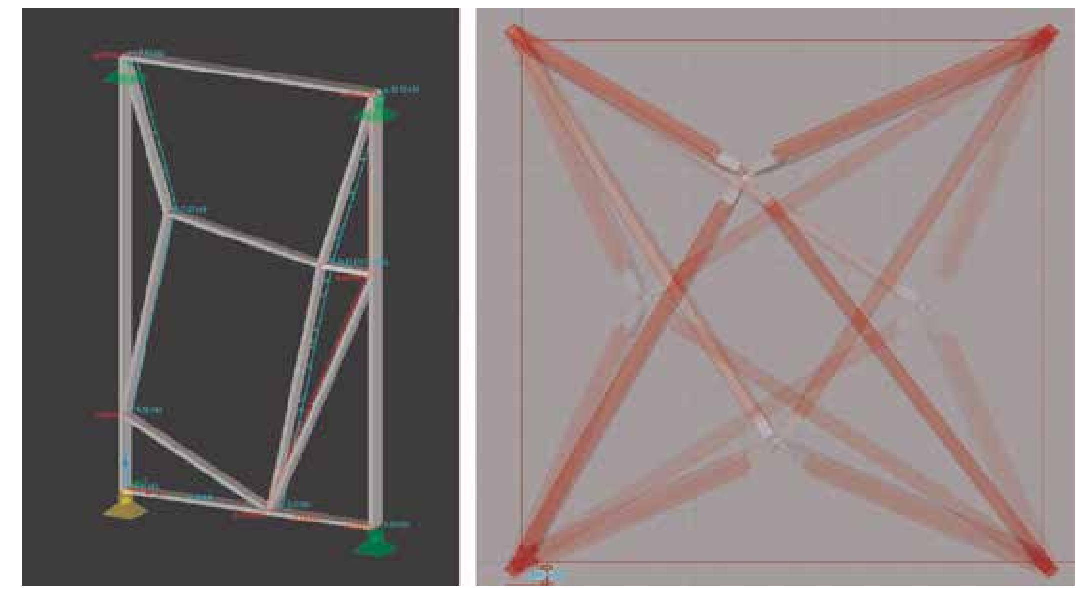

Fig. 6 Node different positioning scenarios

The structural integrity had been verified by finite element analysis to predict the behavior of the nodes. Figure 7 and 8 shows the stress analysis of the node that is connected to three bars. The load case was extracted from the analyzed model.

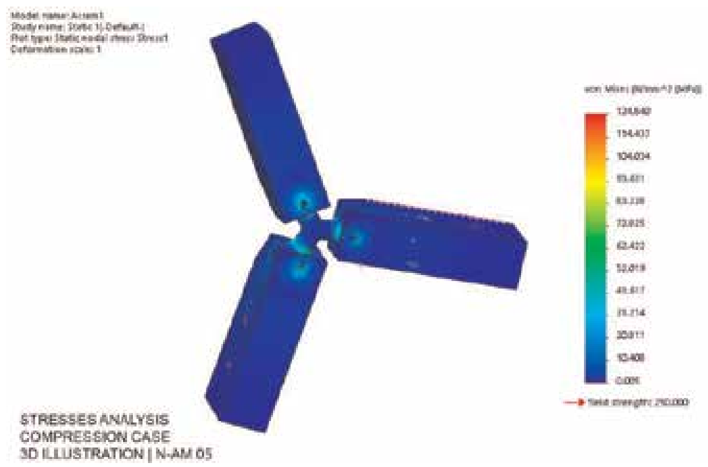

Fig. 7 Stress analysis – Compression case

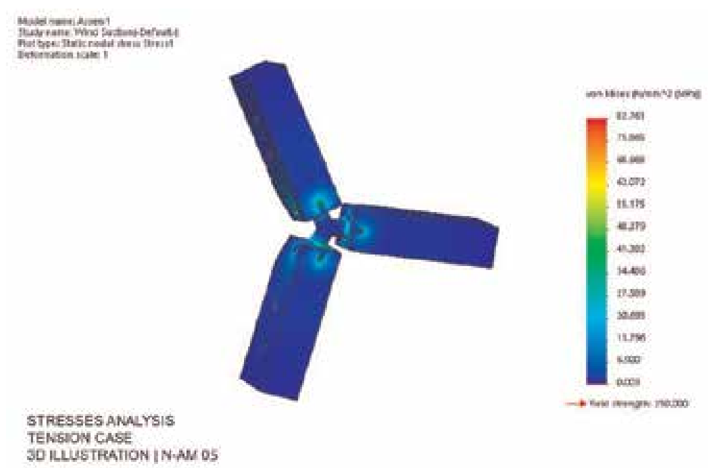

Fig. 8 Stress analysis – Tension case

The rotation caused by the ball connection is locked by screws when the required angles are achieved.

4.2. N-AM 2nd Generation

The 2nd generation idea was released from the traditional manufacturing techniques, and at this point, additive manufacturing and parametric design were used solely to move the nodes from design to physical product. The idea of the 2nd generation is to parametrically generate the node as a volume and use additive manufacturing to manufacture that volume. Additive manufacturing is considered costly in comparison to traditional manufacturing techniques. As a result, topology optimization has been investigated as a cost reduction factor.

In the field of topology optimization, there are prominent algorithms, e.g., Solid Isotropic Material with Penalization (SIMP). Its stress criterion should be as simple as possible, e.g. the stiffness density relation. The 0-1 formulation is a function called density and associated with the design domain on each element in the finite element formulation. The density of 0 and 1 is viewed as solid and void material (Bendsone 2003).

N-AM 10 was the first generated prototype that utilized the aspects mentioned above. The node printed in Stainless steel GP1 using EOSINT M270 machine. The node consists of 4 arms. Each

arm is subjected to tension forces after the analysis; the areas subjected to less stress were diminished.

Fig. 9 N-AM 10 Model

The investigation started with analyzing irregular forms and the digital generation of the connecting nodes. Therefore, Voronoi diagrams were used to divide a free-form surface. Voronoi is called after the mathematician Georgi Feodosijetwitsch Woronoi. It encodes proximity information to help find closest objects to certain points rather than others (Okabe 2000). Voronoi based façade was developed to come up with the lightest structure possible using the Voronoi tessellation rules.

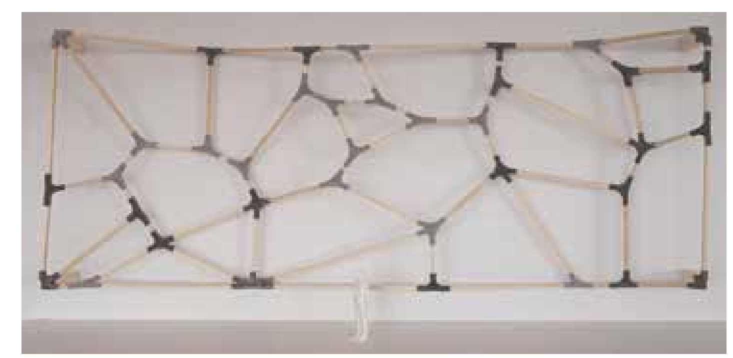

Fig. 10 Voronoi Façade

The nodes were generated using Rhinoceros© and optimized using Solidthinking inspire. The kern of the node had been defined as the design space and made out of steel 355JR. Under the subjected loads that are extracted from

the structural analysis of the facade, the welded and bolted scenarios had been investigated to determine the effect of the connection art on the topology optimization process, in a matter of weight reduction that is resulted from its effect on additive manufacturing costs.

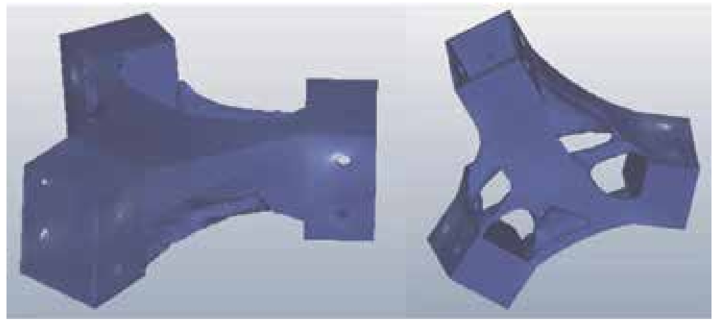

Fig. 11 Bolted node

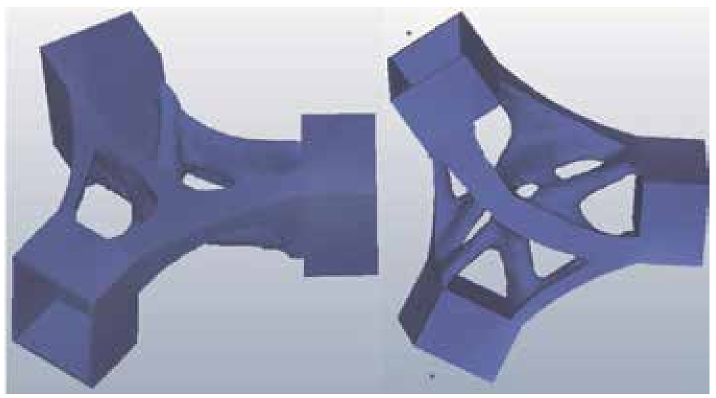

Fig. 12 Welded node

Figure 11 and 12 show a slight change in the generated volume, which provides that connection art can be a factor that affects production costs of additively manufactured connections.

The 1st generation achieved good results reaching a point that approved that having a parametric node is conceivable. The challenge occurred, when the basic shape of the façade element does not form regular geometrical forms. The kernel of the node could not be accommodated because of the irregularities that showed up inside the façade element. Accordingly, a mind-shifting strategy represented by the 2nd generation, had to be followed to overcome these limitations. The strategy is to use additive manufacturing and parametric design solely for the generation of the nodes. Accordingly, additive manufacturing has to be carefully investigated to define its controlling parameters, such as material properties and geometrical limitations, and parametric design has to form the digital generation process that has to be subject to further investigations and developments, such as covering more extensive range of geometrical conditions, and merging topology optimization and structural analysis to the digital generation process.

5 Summary

A middle ground between architects, façade planners, and manufacturer; needs to be achieved. This will keep the compromises to a minimum and will grant a smooth transition from the design phase to the construction phase. This middle ground is achieved through the integration of different planning software and different digital manufacturing techniques. The power of parametric design is increasing, and the gap between design and construction is getting bigger. A new product/system is needed to fill this gap and create a symbiotic relationship. This product/system has to respect the increase of complexity and to try to accommodate these challenges.

With the tendency to have more transparent structures and complex geometries, single layered shells gained more interest. These shells are transformed into straight connecting bars, straight surfaces, and connecting nodes. There is no universal solution for the connecting nodes so far, but many architects, façade planners and façade manufacturers are competing to offer different connecting solutions to the market. 1st generation represented the merge between parametric design and traditional manufacturing techniques to follow a trusted process planning. The results offered an adaptive nodal solution, yet it was geometrically limited to uniform façade elements. 2nd generation represents the merge between parametric design and additive manufacturing, eliminating process planning from the whole process, and widen the geometrical conditions that could be manufactured. The parametric planning is defined through; geometric design parameters – such as form, complexity, and variation of connecting angles-, structural design parameters- such as material properties-, and manufacturing parameters – such as size of the printer and printing angles limitations-.

The search for a parametric node that can ease the design and engineering process of complex façade constructions, is feasible. Many factors need to be investigated to complete the concept. These factors are defined through the whole process of parametric planning and additive manufacturing. For parametric design concept, integrating different façade functions – such as drainage channels and fixation method- is important, as well the relationship between topology optimization, structural analysis, and material properties. This relation introduces material testing to the additive manufactured parts to get more understanding concerning the material behavior. Design for manufacture is the factor that will convert the manufacturing limitations as parameters to improve the digital representation of the nodes. Once these factors are investigated a planning concept for complex geometries can be formulated and with the further development of additive manufacturing technology and parametric solutions, the concept can be further developed.

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