SMART NODES
A SYSTEM FOR VARIABLE STRUCTURAL FRAMES WITH 3D METAL-PRINTED NODES

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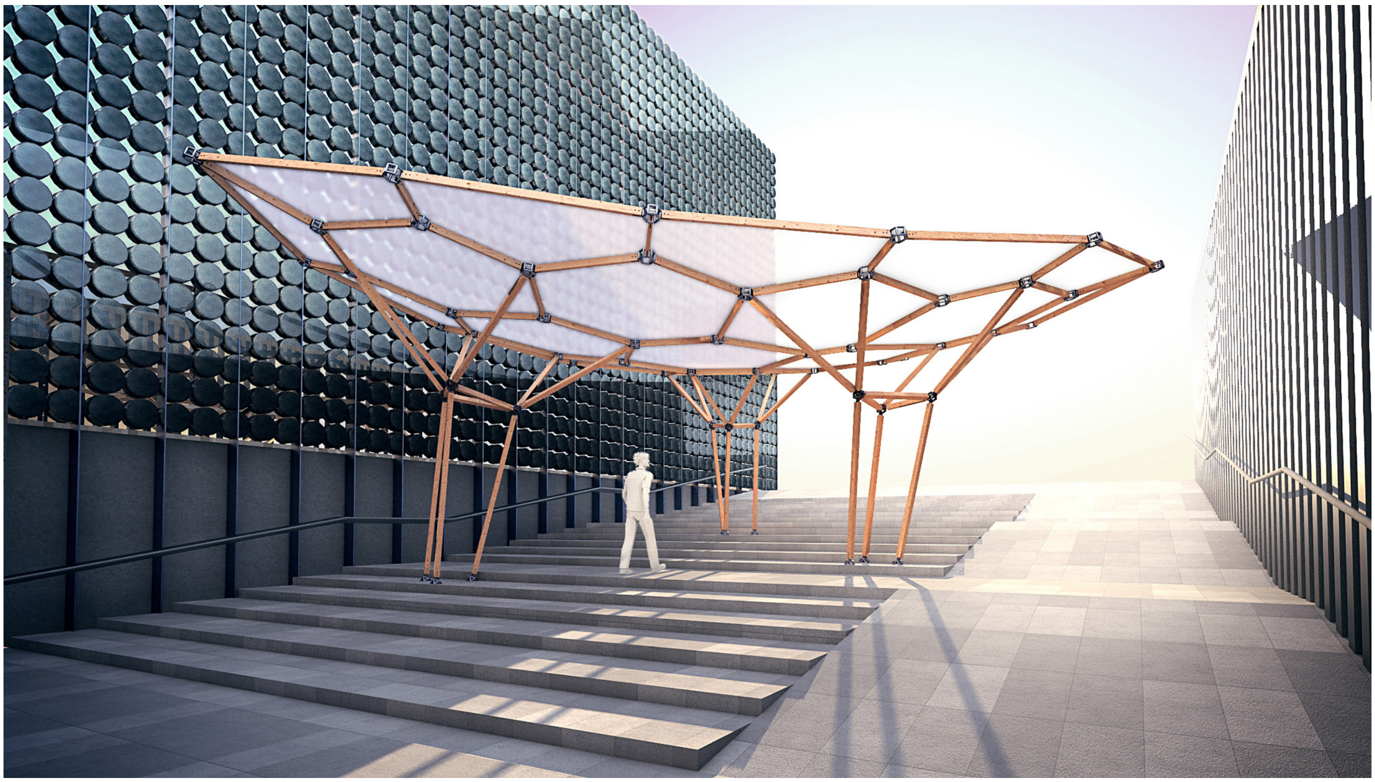


1 A Typical SmartNodes Structure – composed of a set of generic planar panels and linear beams, connected by mass-customized nodes

ABSTRACT

This paper presents a design system for the construction and development of timber structures that use 3D metal-printed nodes. It explains how, through the use of an open-ended design system, small-scale structures are generated from basic geometric inputs. Embedded structural analysis produces load scenarios for the node connections, which are topologically optimized and 3D printed from metal. Such rapid manufacturing promises high levels of geometric flexibility, which can be customized to various geometric and loading scenarios. Both topological optimization for structure and other optimization processes directly related to the manufacturing process allow for material and weight reductions of up to 60 per cent. It is intended that the nodes can be produced in areas of such high-tech production and shipped using existing distribution networks to remote areas where they are to be combined with standardized and widely available timber, thus reducing transportation costs and overall embodied energy. The centralized production of high-tech parts and the incorporated performance analysis and optimization opens up the automated design setup to multiple secondary authors for implementation in various, possibly remote or rural, areas and communities.

INTRODUCTION

"The future is already here, it's just unevenly distributed." (William Gibson 1999)

A number of contemporary architects and critics have expressed concern about the future agency of architects. In order to avoid significant compromises to the architecture profession, it has been widely suggested that the creative adoption and appropriation of new tools and methods will allow for the economical creation of customizable multiples, for example (Celento 2010). Procedural design tools give architects easy access to design and produce serial-variations of parts. As an exemplar opportunity, designing built form with the aid of real-time physics engines has become possible, as has automatic analysis of finite structural elements, bringing a good deal of power from structural engineers back into the scope of the architect. In parallel to this, the rapid prototyping industry is burgeoning and the cost of digital fabrication is dropping dramatically. Currently, however, digital design and fabrication tools are primarily used for high-end institutional or private projects with relatively large budgets. Environmental considerations and large waste production often associated with the construction of geometrically complex parts has led some to question the preference for formally expressive output from digital evolutions. Few applications have been developed to address more economically limited scenarios.

This projects seeks to identify and prototype a system which applies leading design research to a common problem and which could be utilized in a range of situations. A framing system is proposed that uses a mixture of customized, highly designed parts with elements that are low-tech and standardized. By focusing on the nodes where beams connect, the smallest components of such a framing system can be produced with relatively inexpensive digital fabrication techniques. The majority of the volume and weight of the project is composed of conventional products of timber beams and planar panels – parts which are cheap, can be adapted to local supply in a given scenario, and can be assembled with limited onsite skill requirements (Figure 1).

PROJECT OPPORTUNITIES

The desire of architects to engage manufacturing paradigms has a strong history, perhaps best exemplified by Walter Gropius' vision that the Bauhaus embody "laboratories in which prototypes of products suitable for mass production and typical of our time are carefully developed and constantly improved" (1926). Some contemporary commentators in architectural discourse have explicitly updated this call to reflect contemporary modes of manufacturing, most notably the potentials of mass-customization to deliver differentiated elements to mass-markets. Additive manufacturing has much potential for mass-customization and many in the manufacturing field have described the promises of additive manufacturing being applied as direct manufacturing for the production of final parts (Gibson 2010).

In 2014, many patents will expire that have held back the development of some forms of 3D printing technology (Mims 2014). Of particular interest here are those on 3D *selective laser sintering (SLS)* processes, the lowest-cost 3D printing technology, which is likely to result in a significant drop in printing costs using this process. Inexpensive printers are predicted to flood the market in a similar way as open-source low-cost *fused deposition modeling (FDM)* printers, such as Makerbot, have proliferated. In the case of metal laser sintering, it is foreseeable that within five to ten years costs will have dropped to a level that makes competition with traditional manual manufacturing techniques economically viable (Figure 2).

However, although the dropped printing cost will lead to an increased access to the technology, the availability of high-end fabrication equipment is likely to remain limited to areas with high-tech capabilities. Initial investment costs including required operational skills and machine maintenance combined with a still limited product demand suggest that centralized manufacturing plants will offer 3D laser sintering services at low cost. Through currently widely available product distribution networks, finalized 3D printed products will easily be transported around a global network, including to remote areas.

EMBEDDED OPTIMIZATION & DESIGN AUTOMATION

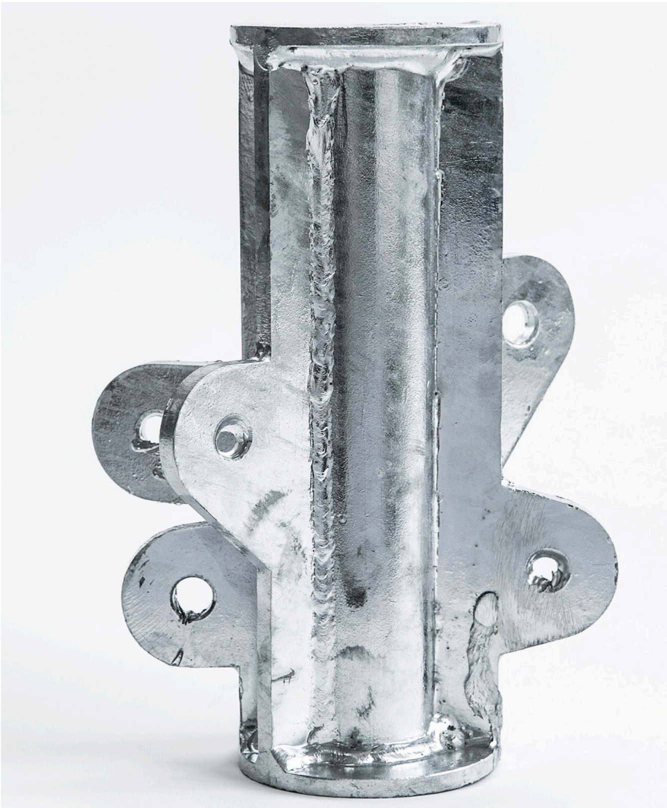
A project that is conceived as a design system is automatically opened up to different levels of authorship. Digital designers no longer work on exact notations of singular objects, but develop "interactive avatars" (Carpo 2011). These informational models are "objectiles"–generic schema that easily allow for multiple object variations. The designer of the objectile is a primary author who relies on secondary authors for implementation. This radical shift in authorship permits the embedding of intelligent feedback systems and optimization routines that are solely controlled by the primary author. A secondary author is then required to input a limited set of carefully selected variables and parameters. As long as his choice navigation is simple enough, the secondary author can remain oblivious to the built-in system intelligence and an optimized object can be produced.

THE SMARTNODES SYSTEM

This project consists of a fully integrated building information model that, from a limited set of inputs, produces topologically optimized 3D-printed nodes that can be combined with standardized beams in the production of a structurally efficient shelter or enclosure.

GEOMETRY

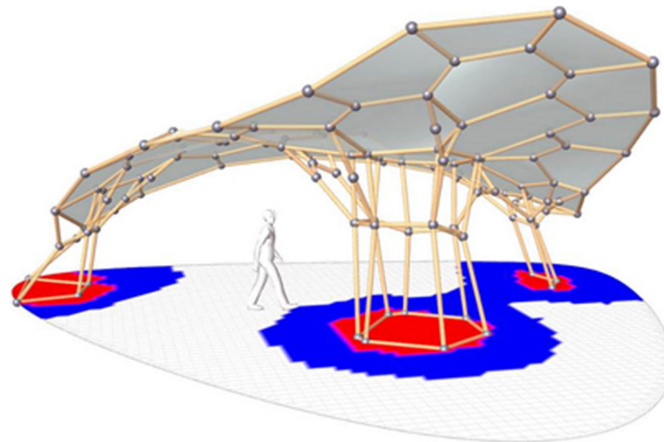
To initiate a design, a series of contour lines are used to generate a planar mesh. This mesh can be painted though the direct input of a designer to assign color code that identifies areas for the generation of substructure and areas where this substructure connects to the ground (Figure 3). From this setout geometry, a bending-active membrane with substructure and ground connections is generated and subjected to inverse gravity forces using real-time physics engines. Maximum panel and beam dimension are used to generate a planar hexagonal panelization from this deformed membrane (Cutler and Whiting 2007). This planar geometry is then used to generate a wire-model of the proposed structure.



2 Precedent Node – Comparing a manually manufactured node (top) and 3D printed node version (bottom)

STRUCTURAL ANALYSIS AND FEEDBACK

The definition of a membrane shape through a digital process of so-called dynamic relaxation produces a shape which is structurally efficient when gravity loadings only are calculated. In designing canopy structures, however, the design system requires that other loadings be considered, primarily wind loadings. This requires that feedback from structural analysis adjust the broader design of the system.In this system, an automated structural analysis isolates worst-case loading scenarios for the structure. These are used to consider design changes, which will allow structural improvements to be made. This is achieved by moving the nodes of the substructure in three dimensions until an optimal scenario with minimized bending momenta is reached. Structural loads throughout the entire wire-model are then recalculated and used for dimensioning of the beams.



3 Design Input – Painted mesh indicating areas for support structure

TOPOLOGICAL NODE OPTIMIZATION

At the nodes' points of the wire-model, a series of connection parts are generated and optimized (Figure 4). Firstly, an initial geometry is created in response to the calculated loads and assigned beam dimensions. A boundary representation of the node is then subjected to forces from adjacent beams. Through the application of techniques for evolutionary topology optimization (Huang and Xie 2010) the geometry for the node is then enhanced by reducing weight and material volume to a minimum in response to load conditions and material properties. Construction detail geometry required for future assembly, including connection plates and pin locations, is all embedded in the node (Figure 5).

4 Example Node - Topologically optimized node geometry

3D PRINTING

The additive manufacture of the metal components adds additional geometric restriction to the nodes. Printing of overhangs or horizontal parts without scaffolding is limited and special considerations need to be made to guarantee sufficient heat transfer from the print to the base during the sintering in order to prevent disintegration of layers within the print. Each topologically optimized node is subjected to a spatial orientation process that reduces the necessary support scaffolding and risk of printing defects.

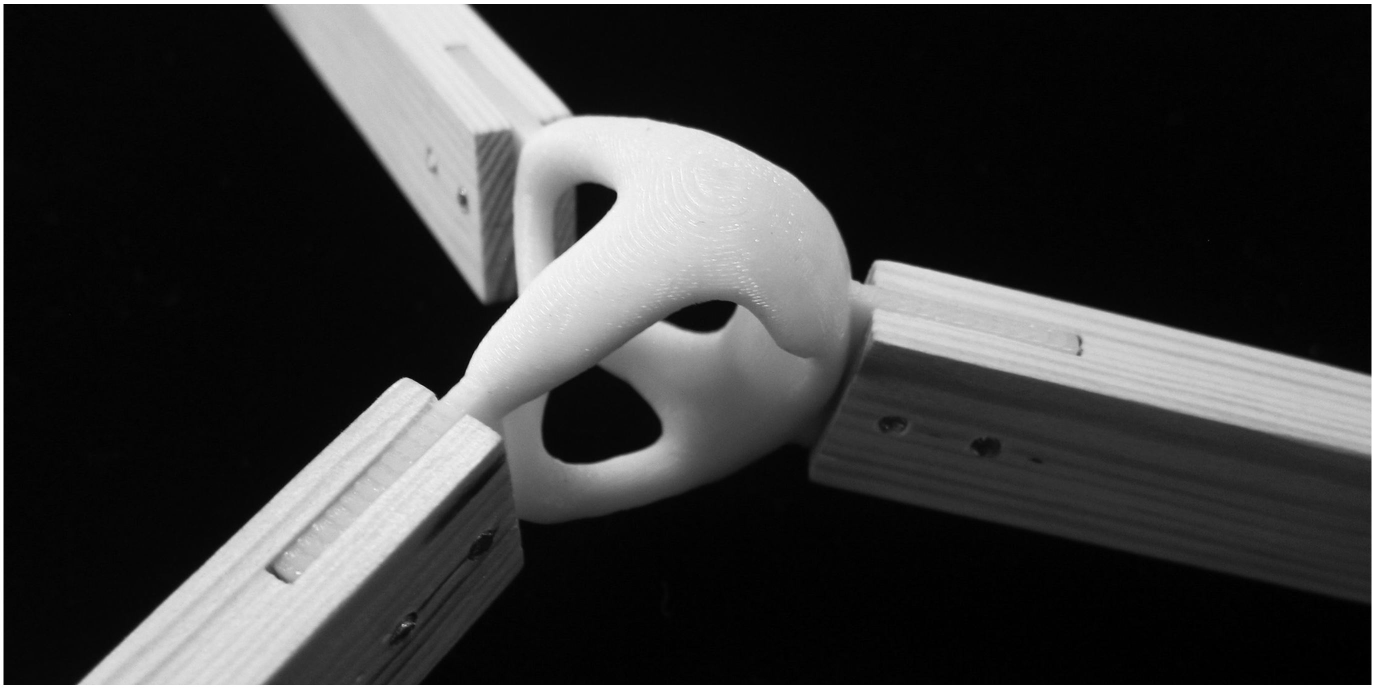
SHIPPING & ASSEMBLY

All unique nodes are marked and shipped to site using existing transportation and shipping infrastructure. Following spreadsheets of data extracted from the 3D-model, standardized beams (specified as timber for early prototyping) and infill panels (specified as acrylic for early prototyping) are cut to shape using widely available generic construction tools. Simple fixing mechanisms such as bolts are used for the assembly of the structure and the panels are attached to finalize the structure.

This combination of bespoke complex nodes with standardized materials requires only the most specialized parts to travel great distance reducing embedded energy. The low-tech input and assembly requirements of the structure reduce the need of skilled designers and builders for the development.

CONCLUSIONS AND FUTURE RESEARCH: UNFREEZING MECHANICAL MANUFACTURING

The requirement for nodes to be fabricated manually adds significant constraints to the geometry, which might be designed through surface-based techniques. The non-planarity of adjacent faces and twisting of beams creates fundamental difficulties in designing and manufacturing the geometry of node connections. These are problems, which are at times solved



5 Scaled Prototype – FDM print of node resulting from generic load conditions

through complex material operations currently at great cost. Rapid manufacturing of customized components offers significant opportunities to overcome these restrictions by resolving geometric discontinuities within the node geometry.

There is significant research to follow, which addresses ideas of optimization for these nodes. Through the use of form-finding techniques for structural efficiency, digital design systems allow for the generation of nonstandard load-bearing components that require minimal amounts of material at any given point of the structure. Currently *BESO optimization* techniques are being employed. Future research will attempt to explore alternative techniques with the goal of better understanding criteria which drive manufacturability.

IMPACT OF DESIGN AUTOMATION

Full *BIM* modeling for singular projects has limited benefit for early-stage architectural design since, unlike the aerospace or automotive industries, the development cost is not spread over a significant volume of products. By introducing a systematic design approach geared towards multiple outcomes from one single "family" of related serial structures, the economies of scale allow for a more elaborate design than a single entity would permit. Further to this, the relative ease of computing optimization procedures with common personal computers allows these to be embedded in the system permitting automatic performance optimization.

Further research will explore the ability for this integrated system to be designed with sufficient flexibility to be applied to a series of desired scenarios.

SHIFT IN ROLE OF THE AUTHOR/ COLLABORATIVE NETWORKS

Projects such as the "One Laptop per Child" are making computational power available to the most remote and underprivileged areas in the developing world. Low-entry software packages can easily be shared and operated through open-source communities allowing easy communication with the most established fabrication hubs globally. By embedding both the architectural design and structural performance evaluation into an automated objectile, the secondary authors can easily become the end users of the objects.

As the cost of 3D printing drops and product distribution networks constantly streamline further, it is conceivable that geometrically complex, structurally optimized architectural design solutions could become accessible to individuals without the intervention of conventional architects or structural designers.

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Structural Analysis: Arup, Melbourne

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Topological Structural Optimization Research: Hamed Seifi, Prof. Mike Xie, RMIT University.

Additive Manufacturing Research, Dr Martin Leary, RMIT University.

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IMAGE CREDITS

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Figure 2. Arup, Amsterdam.

Figure 3. Crolla, Kristof, SmartNodes, 2014.

Figure 4. Williams, Nicholas, geometry by Seifi, Hamed, SmartNodes, 2014.

Figure 5. Williams, Nicholas, SmartNodes, 2014.

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