Non-Uniform Assemblage: Mass Customization in Digital Fabrication

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Abstract

This paper focuses on the development of parametric detailing, mass customization in CNC fabrication and its computational and handcrafted realizations in actualized built work. The projects studied are examples of student and faculty applied research work at Columbia University's Graduate School of Architecture that engage parametric design strategies to integrate digital fabrication processes with manual assembly procedures, including prefabricated components and assemblies. The presented case studies include the design, fabrication and assembly of two full-scale pavilion projects.

Introduction

Historically, prefabrication in architecture carried with it connotations of factory production, truck delivery and crane installations of large-scale modular assemblies. Such assemblies, for much of the 20th century, have been subject to the protocols of mass production, favoring factory built homes assembled from a standardized kit-of-parts. These homes are typically assembled off-site, either in totality or as large sections, and tend to adhere to normative design and construction methods. In addition, by employing standardized parts, the designs must adhere to a predetermined means of assemblage. There is still much truth in Le Corbusier's statement that "architecture is governed by standards. Standards are a matter of logic, analysis and precise study."[1] Indeed standardization was a necessary component for the evolution of the modern and rational architecture of the 20th century and an inherent criterion for any mass-produced product. Traditional prefabrication in architecture, despite Le Corbusier's declaration in 1931 that "[m]ass production is based on analysis and experiment,"[2]has been associated with the repetitive production of factory homes using static elements. As Walter Gropius stated in 1964: "…the idea of prefabrication was seized by manufacturing firms who came up with the stifling project of mass producing whole house types instead of component parts only."[3]

We are now in an age of digital fabrication, whereby the potential output of the Computer Numerically Controlled (CNC) machines does not rely on a repetitive and linear approach to production. With digital fabrication mass customization has become a reality and at times a necessity. Mass customization "proposes new processes to build using automated production, but with the ability to differentiate each artifact from those that are fabricated before and after.

The ability to differentiate, to distinguish architecture based upon site, use, and desire, is a prerequisite to success that has eluded our predecessors."[4] This is antithetical to the historic notion of mass production which "was about the economy of making things in quantity"[5] which inevitably required the architect or client to choose from predetermined parts or accept an inhibitive cost for a custom component.

Contemporary architects often look to aerospace or automotive industries, whose reliance on precision, robotic construction, zero-tolerance connections and ability to create customized products, attempts to enhance or invigorated current practice. The adaptation of architects to design based on the use of digital software and CNC machinery reinforces the conception that prefabricated components and assemblies embody a similar degree of exactness, yet the construction industry has a history of a flexible precision and tolerance at odds with this idea. The question that now concerns us is: can professors and students, typically not privy to the vast resources of the aerospace or automotive industries, utilize and advance digital fabrication and CNC technology?

Resources

In the spring of 2005 the Graduate School of Architecture, Preservation and Planning (GSAPP) created the Digital Fabrication Lab (DFL), by purchasing one 3-axis Techno-Isel CNC router and one Flow CNC abrasive water-jet for the School. The mission of DFL is twofold: first, to develop techniques for merging design and fabrication through digital networks (a design goal), and second, to develop new building systems using CNC technology for prototyping full-scale component parts that structure the logic of larger assemblies (a production goal).

Fig. 1. GSAPP Digital Fabrication Lab.

What distinguishes CNC technologies within architecture is the opportunity afforded to reposition strategically alongside fabrication and construction processes those products architects actually produce, drawings; shifting from loose representations of buildings to highly precise sets of instructions coordinated and integrated into a full description of a building. The DFL has developed three general methods of research within the GSAPP context. The first and typical is through classes that engage the DFL as a means to explore materials and techniques involving CNC technologies. The second is through projects that employ the DFL and its student and/or faculty researchers to explore the methods developed at the GSAPP. The third method is though research funded by industry, grants or through internally developed explorations. Both of the projects explored in this paper exemplify all of these goals.

Case Studies: Introduction

The first project involved the "Trusset," a patented structural wall system invented at the DFL by Phillip Anzalone and Cory Clarke to provide an inexpensive and simple method of manufacturing and building a custom arbitrarily curved enclosure. The opportunity arose to realize a full-scale installation of the system on the occasion of the GSAPP's 125th anniversary in Lowe Library. The project, designed, prototyped and built by graduate students, was run as a semester long technology seminar within the GSAPP curriculum. The students worked on developing panel details as well as the system's assembly and installation.

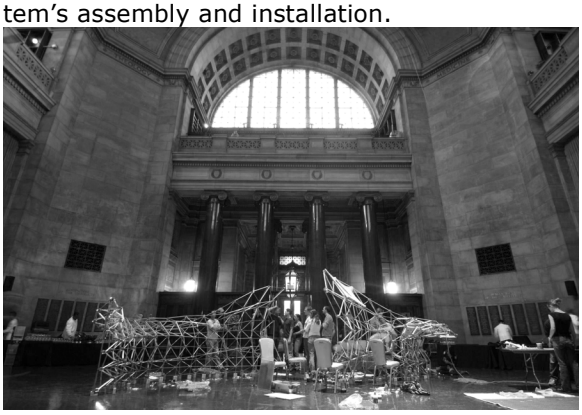

Fig. 2. Trusset installed at Columbia University.

The second case study was a collaborative project during the summer of 2008, involving three Universities (the GSAPP, the Architectural Association in London and the Politecnico di Torino in Italy) and organized by the Torino World Design Capital. Thirty-five graduate students from around the world worked over a two-week period in order to design, prototype and produce a temporary wood pavilion installed in Torino during the period of the design fair "Designing Connected Places." Students worked on developing a design that ranges from the urban scale of the design fair exhibition down to the details of the assembly of the pavilion itself.

Fig. 3. Prototyping the City installation in Torino.

Both projects are based on prefabricated metal or wood components (nodes, struts, bolts, beams, columns or panels) of standardized sizes, provided by sponsors. These two projects have challenged the idea of a simple assembly of a mass produced kit-of-parts through the on-site real time re-conception and modification of the detailing and construction based on design, contextual, environmental and programmatic issues. Ultimately the goal was to reinvigorate the hands-on design approach to fabrication with an emphasis on the digital fabrication, mass customization, CNC technologies and parametric design strategies.

Case Study: GSAPP

The Trusset system for the GSAPP, functioning as both furniture and wall partition, featured two pieces designed to show the system's ability to deal with complex surfaces and torque. These were the results of a semester long design investigation and consequent CNC fabrication through a technology course within GSAPP's curriculum. Ultimately, the final installation at Columbia University was in the school's historic Lowe Library, a classical backdrop in stark contrast with the high-tech trusses.

Space-trusses are highly efficient lightweight structural systems that can span long distances and allow for a high degree of flexibility. Typically space-truss structures are difficult and costly to manufacture, and require highly skilled labor on site for assembly. Through the development of a unique structural detail and custom software, Trusset space-trusses can easily be manufactured with a simple CNC 2D laser cutter and assembled on-site with unskilled labor and a minimum of equipment. The details of the system are manufactured from standard sheet material and can be shipped flat to the site -- making transport efficient and easy.

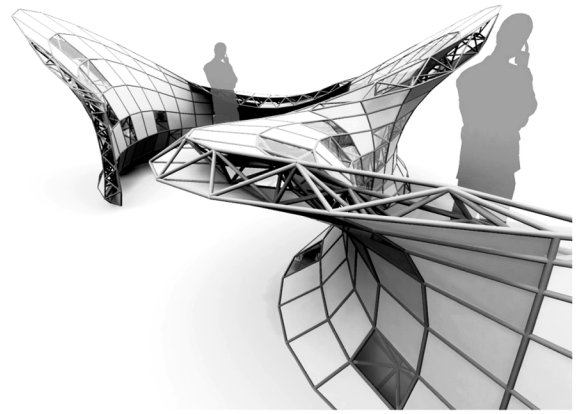

Fig. 4. Design model of Trusset 125th Anniversary installation.

Fundamental aspects of costs, digital fabrication, efficiency and ease of assembly were driving ideas behind the development of the Trusset structural system. The system builds on the advantages of the traditional space-truss, modularity and efficiency, and through refinements in detailing and engagement of CNC manufacturing process it surpasses the limitations typically associated with this method of construction, namely that of cost and form. For the Trusset project each node and strut, being entirely unique, was catalogued digitally prior to fabrication. Once assembled each node could then be efficiently organized in anticipation of assembly.

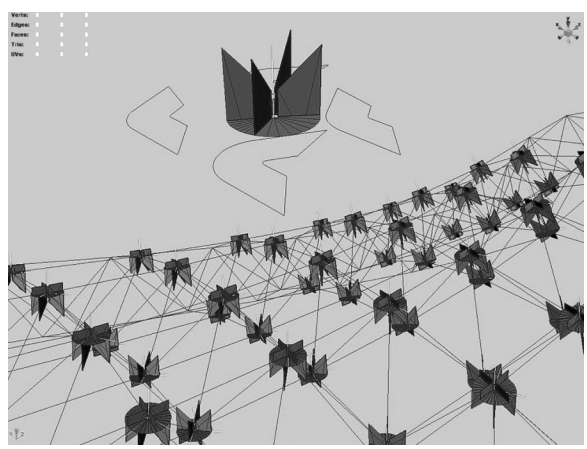

Fig. 5. Parametric model of Trusset installation.

Producing a non-uniform space-frame like the Trusset is an exercise in information management; each member and connection node is parametrically related but unique. Mark Collins and Toru Hasegawa, of Proxy Architects and recent graduates of the GSAPP, generated the

computer model through custom MEL scripts in written MAYA. The scripts extracted UV coordinate values from a pair of undulating NURBS surfaces offset from each other at the depth of the space-frame. In each surface, connecting the UV grid points formed the rectangular outer planes while connections between surfaces yielded the diagonal members.

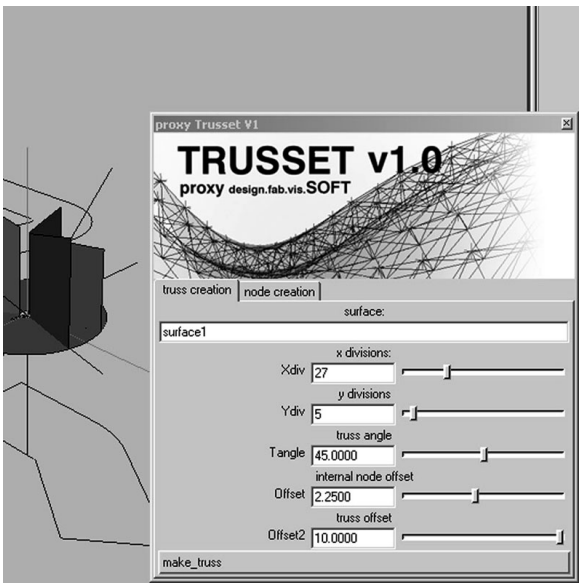

Fig. 6. Trusset software interface.

The octahedral/tetrahedral geometry of a normative space-frame was thus warped to comply with the NURBS surfaces. This yielded numerous programmatic and cladding possibilities while remaining highly efficient materially. Nevertheless, assembly of the Trusset was entirely analog and unforgiving. There was a good deal of handcraft: each custom node, cut from flat stainless steel sheet stock on a CNC abrasive water-jet, were bent by hand and the members, over 1100 of them all with different lengths, were cut with a chop-saw from a spreadsheet generated from the script.

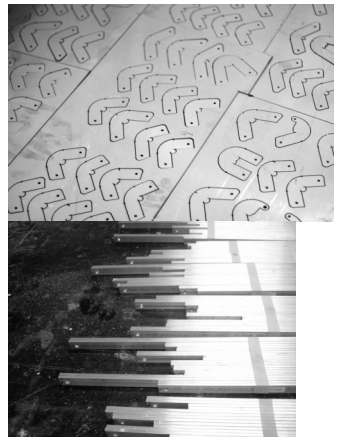

Fig. 7. Waterjet cut nodes and aluminum cut struts

Each part had to be in exactly the correct placement with its neighbors and so, naming of the parts was an opportunity to clarify assembly. The first designation for a node was which plane it lay in. Second, each node had a number corresponding to its location in the UV grid.

Each node connected to eight other nodes: four lying in the same NURBS surface and four lying in the offset surface. The ones lying in the same surface were part of the same UV grid with a roughly orthogonal local orientation. The connection points on these nodes corresponded to N, S, E and W compass directions. The four lying in the offset surface, the diagonal members corresponded to NE, SE, SW and NW. So, a particular part of a node might have a name like: u0_4NE. This would be in the "upper" surface, in the "0_4" UV grid location with a "NE" or North East connection orientation. A member's name would represent the nodes it connects. For example, "u0_4NE l1_4SW" would be a diagonal member connecting the upper surface to the lower from Northeast to Southwest from the 0_4 to 1_4 UV grid points. This naming system allowed the assembly crew to organize and assemble the Trusset, which was more laborious and time consuming than the fabrication time for the parts. One can argue that the strongest aspect of the MEL scripts that produced the Trusset was the ability to automatically generate the part names. Without that functionality, a difficult job would have been impossible.

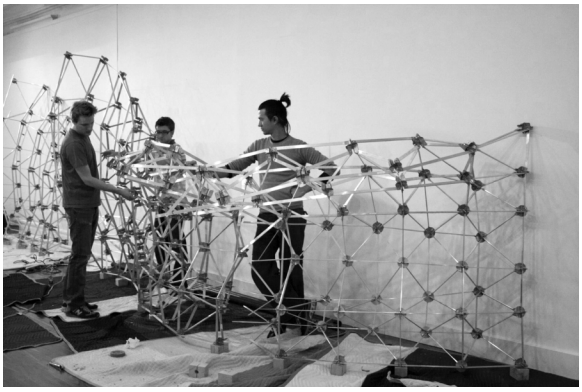

Fig. 8. Students assembling Trusset system.

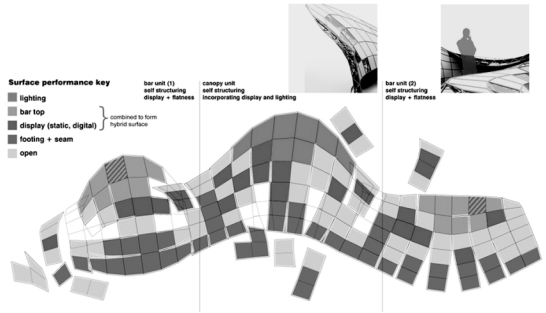

Fig. 9. Panel layout diagram of Trusset installation.

The panel configuration required the fabrication of unique pieces due to the resultant trapezium, a quadrilateral having no parallel sides, shape of the majority of apertures. The panels themselves, having to only clad the Trusset and respond to particular environmental and programmatic conditions, could be fabricated out of novel materials.

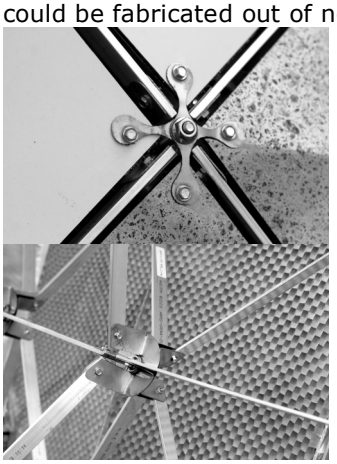

Fig. 10. Panel detailing.

The materials employed included composite aluminum, Panelite (an extruded resin that forms rigid, self-structuring panels), and a high strength, ductile silicone used to cast translucent webbing. Unlike stainless steel and aluminum, students had no experience working with these materials on CNC equipment. This required a series of prototyping and experimenting that ultimately helped refine the design while advancing the knowledge of the lab.

The approach taken in order to complete this project was distinct from the typical ethos of prefabricated architecture. The School did not desire or have the ability to fabricate and assemble the entirety of the Trusset in the Lab.

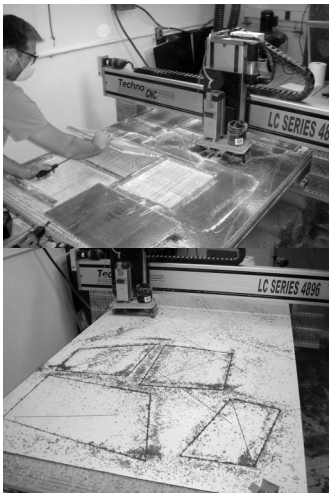

Fig. 11. CNC fabrication.

Nor were we building standard wall units or large components that could be mass produced and then integrated on-site. Thus, the design, fabrication and organization model utilized for this project was that of parts creation and management which was driven by precise staging during the overall construction. By fabricating just the parts we needed at each stage we were able to manufacture and manage a large number of parts within a relatively small shop and short time span. Through this means of production the scale of the final project was not necessarily limited by the scale of the shop. The approach that we adhered to throughout this project was that of maximum output with a minimum means, consciously trying to thwart the typical architectural model that requires resources that are typically out of proportion with the outcome.

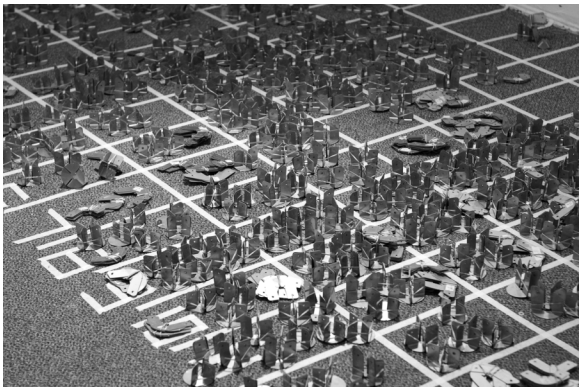

Fig. 12. Trusset nodes inventoried and awaiting assembly.

Case Study: Torino

This second project titled "Prototyping the city" aimed to explore the potential of prototyping as a creative instrument in the production of the contemporary city. The workshop focused on the design and fabrication of a 1:1 architectural prototype acting as the information desk for the six other concurrent summer workshops of the "Designing Connected Places" fair that was held in Pollenzo. The concept of a design prototype is traditionally linked to industrial design and related manufacturing fields. In modern times, the development of new architectural ideas has frequently been explored and tested in relationship to an idea of an architectural type. The idea of an architectural type is today undergoing a radical redefinition owing to the obsolescence of historical models, and being radically reconfigured by new urban conditions, lifestyles, economic transformation, and technological innovation. Prototyping has gained an invigorated architectural relevance and prominence in contemporary architectural culture, education and debate. This resurgence of type and prototyping served as the context of this design workshop.

Fig. 13. Pavilion under construction.

For this project, the GSAPP faculty and students along with their counterparts developed a strategy of parametric design integrated to digital fabrication processes accommodating the detailing of the pavilion based on prefabricated wood components (beams, panels and other elements) provided by the sponsors. Wood, as an organic material, demands a more accommodating approach to prefabrication.

Unlike manufactured materials, wood can exhibit an imprecise structural makeup as well as a tendency to respond to environmental and contextual conditions in an often nondeterministic manner. The first design constraint for this project came from the specific sizes and limited amount of building material donated by the wood sponsor Denaldi Legnami. The students had access to 200 square wood studs at 4 cm x 4 cm x 4 m and 200 wood planks at 10 cm x 2 cm x 4m. What was not determined, thus offering opportunities for innovative design, were the means of connection and the ability to cut or otherwise transform each wood element.

Fig. 14. Design Review Session.

Considering that the schedule for design, prototyping and fabrication was very short, the students were broken into six distinct groups: connections/detailing, ecology/environment, program, parametric design, urban research and structure/prototyping. Initially each group was responsible for producing their own schematic design for the pavilion. After a juried review, a final design was chosen and the six groups worked collaboratively to realize it. The students worked simultaneously to research, program, design, model, test and eventually build the final structure. There was constant feedback and design adaption as each group refined their research and presented new information to the other teams.

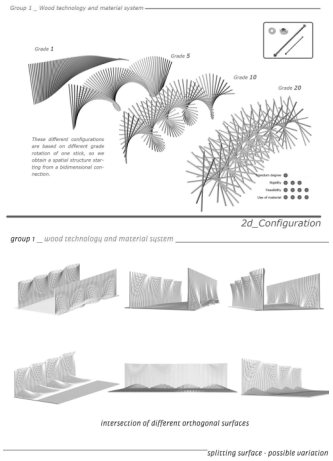

Fig. 15. Parametric study models.

Using the wood elements as a given, a parametric model was developed that explored three distinct configurations of assemblies: branching, meshing and revolving. Numerous iterations for each configuration were developed digitally but only a limited number could be developed physically. Through discussion the parametric model chosen was the revolving configuration, as it was considered the most structurally sound, most adaptable to various connection systems and best utilized the linear nature of the material provided.

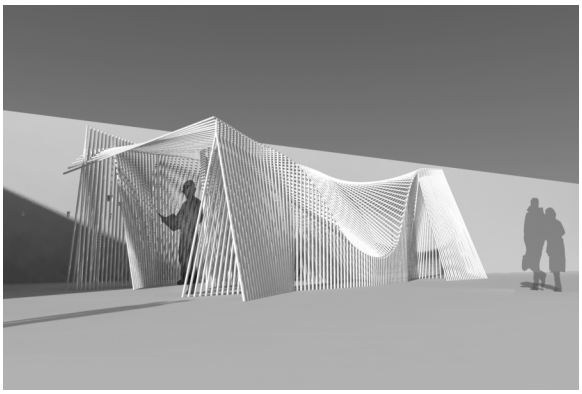

Fig. 16. Parametrically driven design model.

The form was developed as a sectional model that employed a variation of a typical portal frame as its structural system. Through this method of design, the final pavilion evolved from a distinct set of distinct components that relied upon a hierarchical logic of assembly: a series of wood dowels would be connected to create a portal frame which would in turn be connected to create a section of the pavilion. In theory the pavilion could continue to grow so long as there was material and a labor force. This is significantly different from the typical model of prefabrication whereby a final product is realized in the factory and then shipped to the site. Here each building component is assembled on site and placed onto the structure as it is needed. Measurements were pulled for each element and delivered to the pavilion in real-time as elements were assembled into larger components, which were assembled into still larger components, and then finally attached to the structure in a linear manner. This allowed for a much greater degree of customization and the potential to refine the design on-site in relation to the actual context and site conditions.

Fig. 17. Assembly modules awaiting aggregation.

Prior to the production of the final pavilion, rigorous testing of physical models was required. Prototypes were developed from the individual elements to test the performance of detailing and material. This was critical for developing "proof-of-concept" models and refining the components and connections. The purpose of the pavilion prototypes was to test the structural limitations of the given material and the various means of connections.

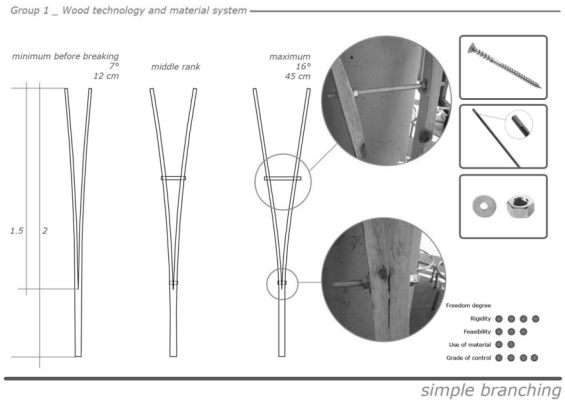

Fig. 18. Basic parametric building element.

It was in this last series of prototypes that the students began to bifurcate a single wood dowel increasing the points at which another element may connect. Through this investigation they were testing the maximum angle of bifurcation, which was dependent upon the flexibility of the material, and how that may weaken the structural capacity of the material. Inevitably the material became too weak but nonetheless the students were able to come up with a compromise: two single dowels were through bolted at one end and then spread apart using nuts and a threaded rod at the opposite end.

Discussion

Despite the fact that both projects utilized digital design and fabrication processes, their final assembly required the distinctly analog process of hands-on construction. In order to mitigate error, at each stage each piece was embedded with the logic of assembly that allowed for an effective human interface.

Fig. 19. Students assembling components into larger systems.

Nonetheless, there were specific orders of operation to be understood. The vast digital continuum that may span an entire project will still, no doubt, rely upon an analog labor force that coordinates potential material variations with the inevitable exactitude of the digital model. At the analog level of assembly, a comprehensive understanding of the relation of each part to the whole is required. The digital model, used for primarily design and fabrication, now becomes a three-dimensional drawing set from which the order of assembly is derived, allowing for infinite points of view and multitude of instantaneous sections, plans and elevations that can be dynamically updated in relation the design or programmatic criteria.

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GSAPP 125th Anniversary Trusset Project

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System Co-inventor: Cory Clarke

Researchers: Mark Collins and Toru Hasegawa of Proxyarch

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Torino 2008 World Design Capital International Summer School "Designing Connected Places"

Prototyping the City -Design Studio

Workshop Leaders: Claudia Pasquero, Marco Poletto Architectural Association, Ecologic Studio London, Caterina Tiazzoldi -Columbia University New York

Local coordination: Cesare Griffa -Politecnico di Torino

Local Partners: Denaldi Legnami s.a.s. Casale Monferrato

Experts: Phillip Anzalone – Columbia University

Assistants: Davide del Giudice, Andrea Graziano

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[1] Le Corbusier, *Towards a New Architecture* (Dover Publications, New York, 1986), p. 148.
[2] Ibid., p. 6.
[3] Walter Gropius, quoted in Herbert Gilbert, *The Dream of the Factory-Made House: Walter Gropius and Konrad Wachsmann* (Cambridge, Mass.: MIT Press, 1984), p. 318.
[4] Stephen Kieran and James Timberlake, *Refabricating Architecture* (McGraw-Hill, 2004), p. xiii.
[5] Ibid., p.111.