Digital Fabrication and Mass Customization for Constructing Architecture: Suggestions from Some Recent Case Studies

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Abstract

The scenario of construction industry is nowadays pushed to evolve due to different factors: first of all the enhanced capabilities of parametric design which enables designers to anticipate technological constraints, secondly the evolution of cnc machines and production devices which allows new degrees of freedom in some types of component production. Those factors influences the construction industry giving new tools to better respond to architecture contemporary request of flexibility, unusual shapes, high performances, personalization of materials and technologies. Digital fabrication – aiming at fastening and improve information transfer from design to construction - and mass customization - a type of production flexible to customer needs at a cost nearly equal to standard products - can offer to the designer new instrument to control architecture construction and introduce innovative procedures or technologies. This paper, after analysing some recent case studies, most of them focused on innovative building envelope components which seem to better take into account these new challenges, gives some suggestions for taking advantage of the benefits of digital fabrication and mass customization for constructing architecture.

Keywords: construction industry, digital fabrication, mass customization, parametric design, innovative technologies
1. Digital fabrication and mass customization in construction industry

In the recent past, placed at the end of the operative chain, strangled by contracts with general contractor and impeached by a traditional company culture, construction industry seemed to have few possibilities for development. Today, the construction process becomes more and more global with a high international competition and the industrial production is necessarily obliged to reply to the requirements of architects in terms of flexibility and innovation.

On the one hand in fact, there is an exponential diffusion of industrialized components, due to opening markets competitivity, the improvement of performances and quality control, but also due to their capability of suiting technological complexity and construction flexibility of many architectural projects. A tendency near to the “technological push”, i.e. to the pressing of new products and systems towards design, pushed by an industry which searches for new markets investing in technology. On the other hand, the exchange between these technological potentialities expressed by the industry and the capacity by many representatives of the contemporary architecture to interpret it in an innovative way is increasing. This tendency can be seen as a “need pull”, a research of satisfaction which can generate profitable interferences with the technological push. In reality, in fact, it is difficult to find models exclusively referred to one or the other, but more often a wide range of hybrid solutions: the genesis of a technology can be found in an intermediate position between the necessity to satisfy a need and the availability of solutions for this need (Verganti, Calderini, 2005). The reasons that have caused the present industrialization state in the construction process, have not only been technical. The technological progress has to be included in the wider context of the structural transformation suffered by the construction sector since the beginning of the 1900 until now. In fact, the push to the industrialization has involved, in addition to the merely technological and industrial aspects, also those social-economical, scientific, cultural and ideological (Banham, 1957; Nardi, 1990)

One of the most important passage of contemporary architectural evolution in terms of representation, freedom of design and evolution, has been the development of the digital platforms, which permit the passage from an arbitrary representation of complex forms to an almost objective one. These computer systems support the increase of technical and computable performances by series of functions linked to the planning and the modelling of the architectural project, which have repercussions on the technical possibilities, accelerating the phase of feasibility. "In a certain manner, nowadays, there is a change from the mental imagine of the project to its instrumental imagine and it is completely different, i.e. the creation is modified by the instrument, by the software, independently of the quality and the performances of the instrument." (Virilio in Burkhardt, 2005, p.8). Livio Sacchi (2005) asserts "(...) numerous software are now available aiming at the management of the modelling of the architectural space, in an evident creative meaning, and there are more and more architects who declare expressly that their projects or buildings would not have been possible to imagine or to realize without the assistance of these computer programs. Thanks to the digital systems, the interaction is still stronger between the preliminary phases of the project process, the following executive operations and at last the construction and the management.” (p. 29). Placing side by side digital tridimensional instruments, such as the parametrical software, to the usual bidimensional
techniques, not only increases the possibility of representation of the project, but adds useful information for the realization of the project, introducing often innovative processes.

This is connected to parametric softwares that enable a more direct production from design drawings, and production modalities, nowadays realized by flexible CNC machines.

Parametric softwares unable to add strategic informations to drawings for multipurpose aims: resolve complex geometries, add data, increase performances and reduce time in production design. Some of them actually used by designers are Digital Project, Generative Components, Grasshopper and Revit. They have different possibilities but most of them can be linked to fabrication thanks to specific scripts (fig. 1).

Figure 1: Construction photo and digital model of SOM, project for Kuwait City. The 3d lamella model was instrumental in the design documentation process.

On the other side construction industry is proceeding towards a production made of custom products but on a large scale, with simplified processings and systems of light pre-fabrication, introducing mass-customization production systems. This term indicates a personalization of products which, recognizing the importance of the requirements for each single project, does not renounce to the conception of efficient technologies at a contained costs. Thus, products are realized to measure for each project and not as standard production for market forecasts. In construction industry this means merging a custom but craft-hand approach to architecture, that has always been the most suitable but the most expensive and time consuming, to a rigid industrialized approach, fast, light but sometime unsuitable for particular architectural solutions. Those new paradigms completely change the perspective of professional practice, integrating in the design phase skills to meet client and architects needs, thanks to a very competent know-how and to lean production technologies.

These innovations are more and more placed upstream the used technology, it is the result of synergies supported by digital technologies, which depart from the division between product and process towards a transversal research, in which both slopes are linked in a delicate balance between the possibilities offered by industry and research and the potential applications. Many systems of the building are concerned by digital fabrication and mass customization process, from structure to roof, but some of them seem to catalyze the major attention: architectural envelope. Those components seem to absorb and enhance availability of informations that parametric design allow thanks to softwares, and will be analysed in the following case studies.
2. Case studies

Traditional forms of buildings is radically changing in the last decades. This is due to a renovated cultural context, new technological boundaries, innovative digital tools and industrial building components. Those factors give a new freedom to designer, who is spurred to experiment more complex shapes, using materials and construction systems according to completely unusual methods. Therefore contemporary architectural envelopes appear more complex not only in their morphology but also in their constructive configurations, raising new technological requirements. In order to meet those requirements construction industry is very soon involved in the design process, in order to dialogue with complex configuration and discretization of shapes geometry, increasing mathematical definition of surfaces, at a very early stage.

Four examples will be analyzed with different technologies. The first one is Post Tower by Murphy and Jahn, with an extruded façade structure, the second one is Zaha Hadid Innsbruck station with double curved glass and steel envelope, the third is Gehry New York office building, with a cold curved unit system façade, and the last one is Atelier Jean Nouvel New Genoa Fair building with a special metal cladding.

2.1 Post tower by Murphy and Jahn, extruded façade structure

Post Tower by Murphy and Jahn, a 160 meter high building that stands at the edge of the city adjacent to the Rhein River. park. The split, shifted oval tower is oriented to the Rhine and the city, facilitating views from the city and minimizing negative wind effects through its aerodynamic shape. In plan the split oval wedges are separated by a 7.40 m wide space. The connecting glass floors at 9-story intervals form skygardens, which serve as communication floors and elevator crossovers. (Figg. 2-3). The tower has a twin-shell facade, enabling natural ventilation, especially in the spring and fall. The glass outer shell protects from rain, wind and noise and allows for placement of the sunshades. Glass from floor to ceiling optimizes daylight. The peculiarity of this project from industrialization in construction perspective is the steel structure of the façade that has been designed and engineered in order to face high speed wind pressure but a the meantime to have a light section of brackets. It has been studied by Thyssen Krupp and Hoesch Bausysteme, two big steel companies in Germany, a special geometry that could allow the external fixing of the glass façade, the possibility to open it for ventilation and a reduced section of steel brackets. This has been achieved by extruding steel bars in two pieces, one with a T shape and the other one with a parenthesis shapes and fixing them together in a unique profile for glass positioning. Extrusion of steel has not been so easy at it needs stronger machines, higher forces, and matrix gets used very fast due to hot temperatures. However this technique applied to steel really allowed a 60 mm section profile for a floor high of 160 metres with strong structural performances. (Fig. 4-5).
2.2 Zaha Hadid Innsbruck station with double curved glass and steel envelope

Zaha Hadid Innsbruck stations is the last project presented in this paper and probably the most complex, from different points of view. Those stations have been completely designed by the architect in Rhino and then produced thank to a file to factory production systems.

The envelopes is a double curved surface, with glass panes, joined to the structure thank to a simple steel and epdm joints.
The moulded, double-curved shapes may suggest that they are made of fibreglass, but the material used for these canopies is far more brittle and unforgiving: it is pure glass. This gives the canopies a polished, lustrous finish, just like ice. Toughened glass also has the practical benefit of being durable and resistant to knocks from falling rocks or trees.

Not surprisingly, the design pushed advanced glass technology to its limits. In construction method, the canopies really do resemble aircraft wings, as the skin has been wrapped all around parallel steel ribs spaced at 1.25m intervals. The big difference is that glass could not simply be riveted to the steel ribs to assume its double-curved shape.

Instead, it had to be made up of a series of rigid panels, all fabricated to the same 1.25m dimensions as the spacing of the ribs. Far more tricky than that, each glass panel had to be moulded precisely to its final double-curved shape, while softened by heat at the glassworks. A total of 850 glass panels were used to cover all four stations, and each panel was unique in its sculptural form. Some of the panels even come with a continuous recess or trough, with a radius as tight as 60mm, to serve as a rainwater gutter sunk into the canopy’s top surface and leading to a conventional downpipe concealed inside.

The glass technology was developed by structural engineer Bollinger & Grohmann, of Frankfurt and Vienna, and manufacturer Pagitz Metalltechnik, of Klagenfurt, although the panels were actually made in China using computer-numerical-controlled (CNC) machines linked directly to the design team’s CAD system in Europe (figg. 6-7).

The basic material of the manufacturing process was a series of flat panes of 12mm thick glass. Moulds were made out of steel rods contoured to the precise double-curved shape of each panel. Then an 8mm thick glass pane was made pliable with heat and laid over the countoured bed as an underlayer to smooth out bumps and imperfections.

After that the final pane was laid over the underlayer. Next, a 1.5mm thick layer of white polyurethane resin was laminated to the underside of the panel to hold the glass together in case it shattered and give it a strong white appearance. All the panels were prefabricated to a tolerance of ±3mm and after manufacture, their precise shape and dimensions were checked by a 3D digital scanner.

The assembly method on site was at least as ingenious and even more complicated. Hadid wanted the curved outer surface of the canopies to be streamlined across all the panels, uninterrupted by gaps, steps or bolt-heads. A secret fixing system was devised in which stainless-steel cleats were bonded with adhesive to each panel so that they would project slightly from the edges. (Figg. 8-9)

At the same time, a 93mm-thick strip of polyethylene that had been pre-formed by CNC to the precise curvature of each panel, was bolted around the outer edge of each steel rib. When each panel was offered up to its final position on-site, its projecting steel cleats were screwed into polymer buffer. Finally, the 25mm gaps between the panels were filled with black silicone that neatly concealed the cleats and screwheads.
A final consideration has been made on the final results that somewhere shows the criticism of experimental technologies. In this case the thin joints sometimes become wide silicon joints not always as previewed in the design phase. (Fig. 10)

Figure 6-7: Zaha Hadid Innsbruck stations. View of one of the station on site and of the modelling of the complex envelope.

Figure 8-9-10: Zaha Hadid Innsbruck stations. View of one of the station on site and of the modelling of the complex envelope. (right) Experimental technologies still shows some criticism on site: in this case some joints became very large to close with silicone due to increasing tolerances.
2.3 IAC building of Gehry associates

The IAC building of Gehry Associates is a glass office located on two side streets in New York City, giving the building’s main facade a smooth, uniform appearance. Horizontal, fritted white bands line the windows, a decorative element meant to control the flow of light inside.

The interest of this project consist on the unitized systems façade studied in order to maintain always a flat geometry, while at the same time having the possibility to ‘twist’ in a position that allows reaching a curved shape of the whole building. Based on a parametric unit principle all the unit are similar but different in order to utilise cell geometry database and similar system design to configure the building shape. (figg. 11-12). Directly extracted from a file design in a parametric software called Catia, quite complex but very complete, curtain wall cells have their own dimension and an exact location in the building envelope structure. In order to build this envelope with a ‘curved’ surface while keeping flat unit system façade, each cell has the possibility to ‘twist’ inside a certain range in order to keep into the correct position. This operation has been first modelled in softwares and then tested on site in order to verify the tolerances and the materials flexibility. On site a manual pressure has been put on the transom in order to fit in its final position and glass at the end of the site operations has the possibility to be shaped for more than two centimeters. (figg. 13-164. This is undouebely a strong evolution in building envelopes technology, because this technology starts from a unitized technology and tries to push the boundary of materials limits.

Figure. 11-12: IAC building in New York by Gehry Associates, 2007. View of the parametric cell design and the mock up test.
2.4 AJN, new Genoa fair, 2009

The new pavilion of Genoa fair is a simple building made of two exhibition levels overlooking the sea covered by a large roof projecting 12 m beyond the quay limit. The lower level is an extension of the existing quay, at +1.00 metre a.s.l., while the upper one is at a height of +14.125 a.s.l. The restaurants and the multi-purpose halls located at an intermediate level also overlook the sea.

The building has been conceived to ensure maximum usage flexibility. Indeed, the two levels can be managed both together and separately, to host two or several exhibitions at the same time. It is completely free of any pillars and therefore guarantees the utmost flexibility when setting up shows and exhibitions. The building develops mainly lengthwise and takes advantage of the unique site features, establishing a constant ‘dialogue’ with the sea and the marina, to which all three levels are inextricably connected: the upper ones by means of outdoor terraces, sheltered by the roof and with a view on the marina, while the lower level, outside the building, turns into a large square along the sea. The relationship with the sea is both direct and indirect. Indeed, the roof is internally lined with a reflecting false ceiling which reflects the image of the sea and the marina on the roof’s slanted surface, taking the dialogue with the sea further, deep into the building.

The entire upper floor is covered by a mirror-finish stainless steel sheet false ceiling. The reflecting surface of the false ceiling is like an artificial sky whereby space is no longer perceived as an indoor area. However, the false ceiling’s main function is to reflect light, resulting in indirect ambient light at all times. Besides letting in light, the false ceiling also reflects the images of the sea and the boats below the building. The false ceiling in reflecting (mirror-finish), pressed-folded different shapes and surfaces have been obtained and combined at different orientations to create a relief-pattern reminding of sea choppiness. This product has been realized using technology coming from automotive, and in particular from Piaggio technology for Vespa motos.

The difficult passage has been to keep down costs while expressing the project idea, therefore 4 moulds has been done that however can be combined in many different ways, creating an effect of casualty that is in reality is quite regular.
Figure: AJN, new Genoa fair. View of the mirror-finish stainless steel with special moulds taken from automotive sector.
3. Conclusions: some suggestions for future developments of digital fabrication and mass customization in architecture

The different forms of digital fabrication and customization of production analysed in the case studies allow some consideration around the concept of innovation in architectural design as a place of 'collection' of information.

The theme of the collection, accuracy and availability of information is therefore crucial in this context. Cynthia Ottchen speaks of the need to find a way to inform the project using 'soft data', ie a package of information that is not excessive for the proposed architecture (thinking at BIM systems) or insufficient to meet the needs of a contemporary project (thinking of the legislative consolidation of traditional materials).

The idea of a strict but not oppressive information in relation to different phases of the project allows to maintain the uniqueness of the architectural project while preventing the excess information in order to create approval and trivialization of constructive solutions, and then architecture. (Ottchen, 2009)

It 'clear that advanced methods of production are not intended to replace entirely the traditional ones, which for some materials and machining conditions are necessary for proper feasibility work. However, it is likely to expect that site will become an increasingly less approximate location of the project construction, especially where constructive methods of assembly techniques will refer to dry and industrial products.

In this context of transformation, construction industry must rethink the roles of different actors. The figures related to traditional contractual roles are changing towards less characterized roles with different specialist skills at different levels of the construction process.

The recent issue of Architectural Design (AD, March / April 2009) dedicated the monograph to the topic of the relationship between the various actors, in this changed scenario of techniques and tools for the project, with an emblematic title 'Closing the Gap'.

Distance between the design developed by advanced studies at the forefront and now increasingly widespread and construction process related to logic and basic contract is still very stiff. This last point, contractual responsibilities, is certainly at the same time the strong and weak point of the whole process of 'information' of the process.

Indeed, if somehow the mutual contamination of project information with other persons is an enrichment of the project and a guarantee of quality, on the other hand the difficulties of regulating this type of relationship, especially in a context like the Italian one, very stiff in terms of procurement, public and not, makes it difficult to test effects of a product customizion and digital fabrication.
Not only technology but also the estimated calculation of an innovative solution are therefore a bottleneck in those situations where, for example, there is a mix of technologies (and products) or it is not possible to identify the dominant technology or vice versa every manufacturer has its specific know-how difficult to compare.

A solution could be for each part to pay a portion of the liability trial, the designer for the definition of the solution in relation to benefits and costs with the buyer, the producer by testing and prototyping with the designer and client the final company with contracts developed ad hoc as well as ad hoc developed technology solutions.

Actually the aim is to find those formulas that will avoid intermediate gray areas contractually harnessing the potential of industrial production in relation to new tools for advanced modeling, in order to diffuse innovative technologies in architecture and to bridges the gap between designing and producing that opened up when designers began to make drawings. (Palermo, 2009).

References


Martin Betchold, Daniel Shodek, (et alii), (2005), Digital design and manufacturing, John Wiley & Sono, New jersey.


Verganti Roberto, Calderini Mario, Garrone Paola, Palmieri Stefania, (2005), L’impresa dell’innovazione, Il sole24ore, Milano.