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“...the time is probably drawing near when a new system of architectural principles will be developed, completely adapted to building with iron.”

John Ruskin (1819-1900)

1 Introduction

Steel is the material of the second industrial revolution, what role can it play in today’s digital revolution? The purpose of this essay is to review the role of steel in modern construction and to assess if architects can benefit from new design tools in order to use this material in a contemporary and effective way.

Construction industry is strictly connected to its cultural, technological and economical context and is therefore a very complex field of study. Steel construction will be framed in such a complex environment with the intention of understanding its present positioning and future possibilities. Residential apartment buildings will be specifically considered. Being this object almost non-existent for no obvious reasons, it may reveal interesting facts about the structure and the biases of the industry.

From an architectural point of view, steel construction, heavily relying on prefabrication and standard elements, puts pressure on the usual architectural design workflow, where plastic and spatial thinking usually lead the game putting structural coherence and rational constructive methods on a second place. The shift from an industrial age to an information age seem to put this material on an ambiguous position. On one hand, it represents a disappearing (dislocating) heavy industry, on the other hand, it is the material capable of turning the most ambitious architectures into reality.
Being steel ideally related to prefabrication, an analysis of prefabricated systems will be carried out, trying to answer why, after almost two centuries, industrialization in the construction industry is not yet a general practice. The concepts of modularity and standardization will be questioned trying to determine if they are still up-to-date. A broader concept of modularity will be proposed in line with the possibilities offered by digital processes.

Since the early times of modernism, the automotive industry as always been viewed as a reference and perhaps architecture can still learn something. Not in terms of aesthetics, but in terms of organizational principles and design strategies. This sector, in contrast to the construction industry, is a sector where the global competition is constantly pushing innovation forward and with no doubts there is matter for thought.

Parametric modelling and associativeness will surely play a major role in the advancement of building systems and an explanation of these methodologies will be offered. The integration between digital design tools and digital production tools will be discussed, trying to understand its importance from a strategical point of view.
In order to demonstrate the exposed concepts, a real case study is showcased. An adaptive modular system is developed starting from an existing project designed in the early ‘00s with conventional CAD tools. This whole process will allow a direct evaluation of a design method based on parameters and associative geometry.

Can modern digital design tools help the development of solutions that are both rational and creative? The hypothesis is that parametric and especially associative modelling, not only have the potential to help the rationalization of both design and fabrication, but also may enhance architectural expression.
2 Steel construction

The general idea between the professionals working in construction is that steel is a material mostly adapted for the construction of infrastructures, warehouses and industrial buildings. Very few architects think at steel as a material for housing, being housing at our latitudes usually associated to concrete and stone. In Japan, North America and partially in the United Kingdom and Northern Europe, the family house erected with a light steel frame is an affirmed reality. Nonetheless, even in those countries, apartment buildings rely mostly on concrete.

2.1 Residential Steel Construction in Europe

Residential buildings represent the 25% of the whole construction industry in Europe and the market represented by the apartment buildings range between 15 and 50% depending on the country.1

Family housing and especially apartment buildings are a very limited market for steel and therefore they constitute an interesting subject of study. Recognizing the reasons behind this situation will allow the assessment of objective obstacles or disadvantages. This awareness will be useful for developing a strategy that may enable the exploitation of this potentially huge market.

Looking at the built surfaces, only 2% of new residential buildings in Europe are steel based compared to the 58% in industrial buildings. This

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2% is moreover an average where the Nordic countries and the United Kingdom play an important role, leaving countries like Switzerland with percentages near to zero\(^2\).

2.2 Steel in Apartment Buildings

Numbers show that steel construction in apartment buildings represents an object that is practically missing from the contemporary construction atlas. An exception are high-rise buildings but even for these typologies, concrete seems to gain momentum. A good example of this trend is the Turning Torso in Malmö where steel was used mostly as ornamentation.

The question behind steel construction in apartment buildings is of an exemplifying nature and the underlying hypothesis is that this specific object may be the one benefiting the most from a development in design and production tools. This evolution will likely make feasible the development of real adaptive construction systems. Adaptability is probably the most important feature missing in today’s industrial prefabrication and it is of fundamental importance in residential typologies.

If the industry will be able to engage in such a change, it is plausible that the whole sector will be reshaped dramatically. For this reason, we will try to understand the advantages and disadvantages of steel as a building material considering these new possibilities.

Wood shares more or less the same constructive logic of steel, is usually cheaper and local artisans are probably easier to find. In order to simplify a comparison with concrete and considering the fact that wood entered in the market of large multi-storey buildings only very lately, this material has been omitted. However, it is important to remind how the combination of these two materials may be a logical choice for fully exploiting new digital technologies. Wood and steel are therefore more complementary than exclusive.

2.2.1 Structural Difficulties

Thinking at possible explanations for the missed opportunity of using steel in apartment buildings, the first reasons coming to mind are related to culture and aesthetics. These arguments will be discussed later, starting first with technical and structural motivations.

A very practical circumstance is the availability of steel construction workshops in the territory. The construction industry is historically a local one and the project clients, contractors or privates, prefer and sometimes have to rely on local craft persons. The steel construction industry, because of the capital requirements and the objects that historically must

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\(^2\) Ibid.
fabricate, is instead much more concentrated and it does not cover the territory the same way local construction companies do.

Always linked to the relationship between steel workshops and general construction companies is the fact that, if a basement must be done, it must be done in concrete and on site. If the scale of the building is large enough, it is convenient to setup on site a systems for the production of concrete and therefore, once this systems is place, it can be very well be used for the entire building. Another difference between general construction companies and steel workshops is that the latter are usually very specialized. If the building needs partitioning walls out of bricks, it will be a general construction company to build them. So, size matters, and for small and medium objects, the burden of managing two separate companies working together may outweigh the benefit of having steel as a building material.

Another potential drawback, always related to the supply and not the demand, is that, usually, steel construction requires more designing hours than concrete and steel workshops prefer to focus on bigger objects for an easier amortization of their initial design costs. Not only so, steel demands an important preparatory work, which is not only a cost, it creates a great deal of rigidity for last minute changes. A construction site can start almost immediately with a concrete based construction. With steel, the same construction site will need weeks or even months, because of the design requirements and the fact that the material must be ordered in advance form external sources.

These two arguments are especially relevant when the project is of a limited scale and when customization plays an important role. Residential building is therefore directly affected. The problem of the additional design effort may be relativized by the fact that usually design represent only 5-10% of the whole building costs and therefore it cannot be that crucial. About the preparatory work, once everything is ready, the potential time gain on the construction site can be very important. However, the real or perceived inflexibility to last minute changes can represent a real barrier. Additionally, the fact that concrete requires less preparatory work is useful in case the delivery date of the construction permit is not known.

From the design side, steel for residential buildings is complicated because it demands a modularity that, while in big objects like warehouses is easy to achieve, it is very limiting in the residential sector. This argument is ambiguous because of the fact that a punctual structural system has always been associated with rationality and the flexibility of the free plan. This may be true for a certain kind of spaces, but in reality, for the typical residential typology, a system based on a raster of columns that formally
accepts little variation may become a challenge. Concrete construction, with its mix of load bearing walls and columns and without a limiting vertical continuity, hides much better structural discordances and exceptions.

Other problems may arise from the unfamiliarity of the solutions offered by the steel industry. It is sometimes easier to invent a detail than looking at the market for an external solution. In addition to this, it is worth mentioning that is difficult for an unexperienced designer to draw steel constructions with generic CAD tools: drawing a slab is surely an easier task than detailing a steel connection. Modern CAD packages are changing this situation, lowering design costs and allowing a simpler conception of steel-based structures. Nonetheless, there is an important inertia and the architectural profession is still adapting to this new technologies. The fact that these tools are available does not necessarily mean that they are generally used.

As a conclusion, the perception of the public toward steel is ambiguous. In cultures where the house is not only a long-term investment but becomes the physical expression of the household, the building material should communicate these same values. Steel, being linked to the imaginary of the industrial production and therefore to an idea of obsolescence, struggles being accepted for housing.

2.2.2 Present and Future Scenarios
The Swiss centre for the rationalizing of construction (CRB) provides a catalogue of construction costs based on a broad selection of buildings already built on the territory. One of these publications refers specifically to residential buildings, unfortunately, being steel construction virtually absent in this category and being concrete the dominating material, an objective cost comparison between steel and concrete is difficult to make. However, looking at the costs' structure in the construction industry and considering that the load bearing structure represents not more than the 20% of the whole construction costs, it is possible to argue that at the present state of the construction industry, steel and reinforced concrete compete at the same level with no one having clear economic advantage over the other. A partial proof are the many functional and speculative buildings that, in the same territory and for the same functions, are built in some cases with steel and in others with concrete. The scale of these buildings may level the field more than the case of apartment buildings, in any case it is clear that there is not an obvious winner.

If from an economical point of view steel is positioned in a similar way than concrete, for apartment buildings the latter is more appreciated from the public and from architects because of its design flexibility. While this is a
fact, steel is probably the material that can better interpret the shift of paradigm in the construction industry represented by digital processes. Steel construction, because of its nature, is strictly linked to prefabrication. This aspect has sometimes been a limit in the past, but with the new manufacturing technologies, this can now be turned into an advantage by using the full potential of this specificity. Automation cannot be easily applied on a construction site and a building system relying mostly on a fabrication made in a protected environment may profit from this. In order to gain a unique competitive advantage over concrete, both conception and design of steel structures must be integrated into an automated workflow.

Steel is not only a material particularly suited for prefabrication, it is a material particularly suited for automated prefabrication. Standard profiles with little tolerances have been on the test benches of robotic fabrication for years. In comparison, engineered wood, often seen as a material suitable for robotic production, comes with tolerances that can be a problem and must be handled. Steel, on the contrary, is ready for automation out of the box. Self-adapting robotic systems and flexible automation are in developments, but while these systems remain matter of the future, steel is already capable of the highest degree of automation with the present technologies.

2.3 Rethinking Residential Steel
A balance between an expensive high-tech use of steel and a “one size fits none” modular building system must be find. New possibilities arising from digital conception methods may create new opportunities in this direction. The conditions necessary to succeed will be the study of new flexible building typologies and the rethinking of living units and spaces. Shared surfaces and a more flexible use of the built space may play an important role. Society, families and the work environment changed considerably during the last decades in terms of flexibility, but residential typologies did not to adjust to this change. In Switzerland there is a trend for larger surfaces per capita, but the way this space is subdivided changed very little during the years. There are interesting experiments for student housing but general developers, as one may expect, chose to remain very conservative.

Mixed-use buildings are another object where steel plays an important role. In commercial and administrative spaces, steel is often appreciated for its modularity of surfaces and its flexibility into accommodating technical equipment. It would be interesting to test if this versatility could be used in residential objects too. The requested spaces and the need of flexibility in housing are of a different nature, but new typologies could be developed abandoning the usual standards. Steel could be used in a way
to generate spaces that could not be achieved with concrete: spaces flooded with light and adaptable to change. The lack of steel in apartment buildings seems to be the consequence of both a cultural and self-imposed design limitations.

Steel construction is strongly connected to cheap corrugated steel sheets, impersonal industrial spaces and other objects that are not valorising the material for its expressive qualities. If we exclude high-rise buildings and concept architectures, only few examples in the history of modern architecture are able to change this impression. It is necessary to avoid the association of steel to simple and speculative industrial buildings, eliminating all the elements linked to this imaginary. Corrugated metal
sheets and external steel treatments must be reinterpreted in order give them a fresh look. The steel building should be a differentiated product, communicating a lifestyle different than the one expressed by other construction materials. Exposed exoskeletons, transparent structures permeable to natural light and the possibility to adapt it to future mixed functions should be embedded into the design from the beginning.

2.4 Toward an Adaptive Steel Construction
Steel structures are characterized by two different conception methods. One is based on a light frame usually composed by cold bent profiles and the other is based on a heavy frame made by hot laminated profiles.

Prefabricated steel construction of medium-small objects often relies on light frames. The cellules made by these light frames become the modules and these modules are then assembled in order to create the whole building. A bottom-up strategy is used in combining the different modules and a top-down strategy is used for fitting single low scale components into every module. This strategy is applied today in both modern fully integrated prefabrication processes and in conventional on site construction. In the past, visionary experiments relying on the idea of combining modules have been realised in objects much bigger than a single family house, unfortunately, because of the complexity and the impossibility to rely on flexible design tools and fabrication, the result was mostly a failure.

The possibility to think in terms of flexible and adaptable spaces using frames with big spans, does not seem an option which has been much explored in the residential sector. The use of a clearly separated and performing load bearing structure, would make possible the division of the building into a superstructure and a substructure, introducing hierarchies and thus providing the conditions for flexibility. In order to use this flexibility, floors should become flexible components creating a shared space for present and future technical equipment. Dry construction principles are consequently a necessity and should govern the project at every scale.

Adaptability means the possibility of easily and cost effectively adapt to present conditions and future needs. It is possible to imagine that big free spans could be used not only for the creation of new dramatic urban typologies, but also for allowing last minute changes in the mix of the offered programs. It is possible to imagine a promoter being able to change on the fly the offered mix of apartments, replacing duplex with studios depending on the market demand. This is already happening for offices and commercial objects and the technical, legal and design difficulties to overcome in order to make this happen in residential spaces do not seem too prohibitive.
It is possible to imagine the complete redesign of an apartment typology in a cost effective way or typologies growing with their occupants. A young couple could buy a generous open space apartment and with a minimal investment transform it in an apartment for a family of four or, vice versa, and old couple with grown up children could decide to split their apartment in two and to rent one of them. These ideas are nothing new, but today’s design tools may help to finally make them real. Extensions, adaptations or reconditions are today a cost nightmare, generated by the fact that, often, two different construction systems must be put together creating costly technical difficulties. In the next chapter, the idea interface compatibility through associativity will be introduced allowing the possibility to design and replace components just by knowing the design algorithm behind them.

Last but not least, combining the lightness of steel with the possibility offered by digital tools to adapt it smoothly to every location, will make this material the perfect choice for working on existing buildings. Thanks to laser scanning, there is today the possibility to create structures fitting perfectly into the existing without having to work on site. This market is potentially a huge one. On one hand, aging real estates will demand in the future continuous interventions and on the other hand, the densification policies that are in place in this country will push more and more the expansion of the existing buildings.
3 Prefabrication

Change in the construction industry occurs extremely slowly because of the characteristics of the product, its complexity and its extremely long life cycle. Not only material reasons are responsible for this situation, the construction industry is often defined by a business culture afraid to change and reluctant to invest in research and development.

For having an idea on how much the construction industry differs from other industries, it is enough to see that in Germany, the average R&D annual expenses per employee in the construction are 590€, compared to 6620€ for the mechanical industry and 30290€ for the aerospace industry. Another interesting indicator is the capital intensity. In the construction industry, the relationship between the stock of capital and the yearly added value is six times lower than the average of the overall economy\(^3\).

While the productivity of labour almost doubled in the manufacturing industry during the last 40 years, in the same period, the productivity in the construction industry not only was stagnant, it declined worldwide by a good 20\(^4\). Researches done in order to assess the causes of this decline identify problems like the excessive fragmentation of the industry, the more aggressive completion schedules or a procurement system based on competition rather than cooperation. It is a fact that today projects requirements are more complex than in the past and it is a fact that this complexity is matched by a poor data management, still largely based on paper documents produced by a team more and more fragmented. Whatever the reasons for this situation are, housing is the single most important investment in the life for a person or a family. Having a construction industry that is failing to incorporate technological improvements into their processes calls the whole sector into question.

Automation and computer controlled processes for on site construction are still a subject of future developments. Therefore, the key to overcome the structural problems of the sector is today to turn as much as possible into industrial prefabrication. There are examples of industrial and organizational methods successfully applied to on site construction, but prefabrication seems to be the easiest way for taking direct advantage from the productivity gains and quality improvements other industries are showing.

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3.1 Prefabricated Building Systems

A building system is a general term used for describing the production of building elements, whether on or off site. The term prefabrication describes the off site manufacturing of those elements. Prefabricated building systems are therefore the systemized manufacturing of building elements that happen off site and that is usually related to industrial processes.

In general, a building system is used for a quicker construction on site, cost and quality control and a better organized workflow. Prefabricated building systems add to these factors a controlled environment which leads to a reduction of labour and additional time savings on site. The possibility to always have optimum working conditions, allows improved precision and quality control and the saving in working hours on site, usually more than compensates the logistics costs due to the transportation from the factory to the site.

The history of industrialization of building systems is a global and long term phenomenon. The process took very different outlines depending on the needs and the possibilities of specific geographical and cultural contexts. It is therefore difficult to gather a general view. Nonetheless, it possible to acknowledge that the industrialization in the construction industry is globally a limited reality. There are industrially manufactured components and building systems, but these systems are seldom integrated into industrial processes leading to the final delivered building.

The degree of industrialization in the prefabrication of system building may vary. The distinction between systematization, prefabrication and standardization is fundamental. There are prefabricated solutions like the ones offered in Switzerland by Renggli AG that provide unique designs that today’s standard industrialized processes cannot deliver. These unique houses still benefit from systematized construction methods but use very few standardized components.

Prefabrication, ensuring a central quality control, may lead to big gains in terms of productivity. The next pages will deal with the idea that digital processes may make the concept of standardization obsolete. In doing so, they will eliminate the limits of prefabrication in respect to on site construction. Architects usual fear prefabrication because they think it may limit creativity and in general may put them out of business. This is not necessarily true, prefabrication may allow architects to control more tightly their creations and thanks to the development of technical standards they will be able accumulate knowledge in fields where they now have little control.

Industrial prefabrication speeds up the production process significantly, but at the moment is adopted mostly in suburban or rural areas where the
terrain is cheap and the site constraints are less important. Usually this happens because industrial prefabrication, in order to make industrial mass production feasible, imposes a limited range of choices for components such as façade elements or structural elements such as wooden beams or steel trusses. The architect’s aims of achieving individuality and artistic expression suffers from today’s modularized prefabricated building systems. On the contrary, if these same elements could be customized on demand, he could gain a great flexibility in design as the building systems would offer a high standard of quality compared to on site construction.

3.1.1 System Differentiation

The discussion between off site and on site construction is only part of the game. An important factor impacting on the perception of the public is the design differentiation. In many cultures and in this is very true in Europe, the house is not just another good and differentiation is quite important. A unique product is still perceived as a handcrafted work of art and repetitive industrialized houses do not represent the ideal of a beautiful home.

In cultures where housing is perceived in a different way or the fundamental values of the society are different, differentiation is not an extremely important dimension. In North America, for example, because of the historical high mobility of people, housing is mostly a commodity and standardized typologies flood the peripheries of the cities. In Japan, where individualism is not as important as in western societies and uniformity is a positive fact, the family housing market is dominated by prefabrication and undifferentiated typologies.
These undifferentiated buildings are built with building systems that included all necessary calculations and authorizations as part of the package. However, the degree of industrialization can be very different. Most of the building systems simply provide industrialized elements or components that must be assembled on site. Only few examples, like the Sekisui Heim or Toyota Home in Japan, rely on an almost complete automated fabrication process.

Taking the example of North America, less than 5% of all homeowners have spoken to an architect and most houses were planned by developers employing whenever possible standardizations both in terms of logistics, production and design. In the case of developers, the final built product must also have good and assured marketability, meaning that any experiments with the appearance of the house can easily lead to a financial failure. The decision to go stylistically mainstream is therefore a logical one and the result is a very limited innovation. The North American idea of a house comparable to a consumption good, prioritizes economic considerations. The low profit margin of individually designed and manufactured buildings, leads to the fact that the development toward a stronger standardization is considered an advantage for everyone.

In general, whether or not the society is an individualistic one or gives particular attention to its houses, it is not impossible to create good architecture and to repeat it endless times. The problem is that good architecture very seldom can abstract from its surroundings and therefore the possibility to introduce variations is extremely important, especially in Europe where the impact with the existing built environment cannot be neglected.

The public’s idea of prefabrication as an industrial product with an intrinsic obsolescence may be a barrier, but if prefabrication would mean better quality, details and possibility of choice, prefabrication would surely be considered fashionable. The problem of prefabricated architecture today is that not only it looks standardized but cheap.

Critiques point out that prefabrication come with a loss of local typology or materials. In the globalized world it would be necessary to specify what a local typology or material is, nonetheless the general opinion would say that this is a truth. However, there is no reason for this to this limitation to exist. Local typologies can be embedded into the design as well as materials. The only requirement is a flexible design system and today’s digital technologies provide just that. There is no legitimate impediment into meeting today’s building standards with prefabricated construction, both formally and technically.

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3.1.2 Innovation in Prefabricated Systems

In the last century, visionary experiments in prefabricated building systems got public attention but they kept being experiments. Prefabricated systems are usually associated with boxy, orthogonal shapes and rigid grids. This should not be necessarily the case, on the contrary, the possibility to build the required components in a protected environment should allow the experimentation of forms and solutions while keeping costs under control.

The language brought by modernism at the beginning of last century, was a direct transposition of the industrialized products of that era and the limitations of these very products finished for being embedded into the architectural design. Interestingly, although the industry offers nowadays better technical possibilities, with a sort of inertia, we still keep reproducing that same aesthetics. The discussion is not whether this circumstance is good or not, what is important is to acknowledge that if in the past these forms represented the direct expression of the industry of mass production, today it is merely a matter of choice.

Despite the fact that most architects use digital design tools, they are often afraid to adopt a digitally governed building construction process, fearful that this would have a detrimental effect on the quality of their work. The fear of a uniformed manufactured product is promoted by the idea that such tools may limit their control over the detailing and the overall architectural expression.

A challenge and an opportunity is today the customization of systemized building. Uniform and unliveable housing developments of the past left standardized system building with a stain difficult to delete. Today, the right implementation of CAD systems makes possible to resolve more and more constraints and to achieve an important level of adaptability. Tools for managing data and processes are today widely available, and they are a key feature in increasing productivity in both designing and planning. The integration of logistics, transportation and assembly into a whole designing process may help overcoming most historical coordination problems and losses caused by nonstandard details and requests.

The coordination and standardization of the interface between design, fabrication and assembly, which is necessary for achieving a building construction completely controlled by CAD/CAM systems, is still in its relatively early stages but is in continuous and fast development. CAM can theoretically directly translate a design into a product and even if its application in the construction industry is still limited, many iconic contemporary buildings already made good use of these new possibilities.
3.2 Modularization and Standardization

The word module comes from Latin and it describes a unit or a standard for measuring or proportioning architectural elements. In fact, modularity has always being associated with the idea of a standardized dimensioning of structures and components. Le Corbusier, for example, with his *Modulor*, was focusing on dimensions, trying to find a universal system of proportions derived from the dimensions of the human body. This focus is easy understood within a mass-production mind-set and was coherent with the limited possibilities offered by the manufacturing industry at that time.

There are industries where the products must be standardized because of production constraints or simply because their market is not on-demand. The construction industry, being an industry with a high mix of parts and low volume, clearly represents a case where a novel approach on standardization could be highly beneficial.

3.2.1 Types of Modularity

Abandoning the original restricted meaning of the word module, today the term may stand for a standardized component of an overall system and this component can be further broken down into separate elements. We can therefore broaden the concept of modularity as something else than the standardization of dimensions. A module can be a large group of elements which are physically coherent as a sub-assembly and therefore can form an independently operable unit that is part of a bigger structure.

What we usually have in mind when we think about modularity is the bottom-up approach where the whole is composed by simple and repetitive assembled elements. However, we seldom think at the modular systems generated by top-down approaches like frame and infill strategies used for example in the aircraft industry. In the section devoted to associative modelling, the difference between a bottom-up and top-down approach will be better explained.

In industrial prefabricated systems, the design is very often generated from a grid. This grid enables the definition of a three-dimensional system of coordinates capable of defining intersections, gaps and surfaces. This design based on grids is almost universally considered the prerequisite for the use of prefabricated components. Within this paradigm, the overall grid system is the defining force and the individual repetitive entities represent the basic modules.

This description seems to define a top-town strategy, unfortunately, a strong and not necessary assumption governing the industry is that this grid must be regular, orthogonal and governed by basic measurement units. In conclusion, this grid, instead of being the driving force shaping all
other components, becomes a mere representation of a bottom-up strategy where the modules are imaginary boxy shaped entities.

Historically there are good reasons for an orthogonal and regular grid. Until very recently, designing and manufacturing tools were not at ease with geometries differing from orthogonality and the measurements units were helping to mass produce elements coming out from manually controlled machinery.

With today’s digital revolution, this situation is changed and this grid does not need to be regular, orthogonal or governed by standard measurements anymore. As long as the rules governing this grid are known, we can use digital tools in order to navigate it and use it as a regulating system. The technology is here, immediately available, but the inertia of the profession still pushed architects and builders to think in terms of boxes as if the Cartesian coordinate system could handle nothing more than a cube or a right angle.

3.2.2 Superstructure and Substructure
Designing architectures with a clear superstructure and a substructure would enable the introduction of hierarchies, making possible a modularity which is not a simple repetition of standardized components. A superstructure would serve as a platform permitting customization by

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M.C. Escher, Distorted Grid, 1956
James_Wines, Highrise of Homes, 1981
further infill and therefore making possible top-down infill strategies on many levels and scales.

3.2.3 From Size Standardization to Interface Compatibility

In Toward an Architecture, Le Corbusier states that architects must develop standardized forms, which they might refine in function and aesthetics, thus allowing for continued progress and refinement. Le Corbusier compares the development of the Doric temple to the evolution of automobiles. The underlying principle is simple: using a standard purpose, the form can be refined, possibly into becoming a classic. He dreamed of mass produced houses where the components, like for the automobiles, are built in modern factories. In order to achieve this goal he offered a flawless receipt: size standardization.

Considering the possibilities offered by modern design and production tools, the concept of modularity as a standardization of size and shape seems to be not so fundamental anymore. The real challenge is today the compatibility between components. Using computer controlled manufacturing tools, most parts can be easily produced in order to fit specific dimensions and performance standards. However, the compatibility between components produced by different manufacturers remains an issue that must be addressed and represents a real bottleneck.

In every building, there are always custom handcrafted parts or components that must be built as an interface between different industrial elements and between those elements and the load bearing structure. Windows, doors or technical equipment: these are all examples of industrial products with connecting details that widely differ between manufacturers. These differences imply that every construction detail must be redesigned and reengineered every time in order to accommodate the new specific interfaces. Not only this fact create a loss of productivity, it creates most of all a potential source of errors and defects.

A solution to this problem can be the introduction of a paradigm of associativeness for the design of interfaces. The concept of associativeness will the better explained in the next pages but the basic idea is that a final design can be derived by a general set of operations and rules. If the manufacturers could agree on the set of rules, it would be possible to produce compatible interfaces adapted to the most different usages without compromising the specificity of every product. The dimensions and the general appearance will be able to vary, but the design logic, the “receipt”, will remain the same. This would allow everybody to design compatible interfaces just by entering the required parameters and let the CAM machinery creating the required set of parts. It is always a matter of standardisation, but the difference is that this kind of
standardisation will be done not at the level of the design but at the level of the design system.

3.2.4 Innovation by Adaptive Modularity
Instead of developing a single building system, with the available technologies, it becomes more interesting to develop a design system driving a generic family of building systems. Modularity in the digital age must be understood not as the repetition of similar components but as the integration of different ones.

Nonetheless, even within this new notion, modularity remains an important concept affecting the whole life cycle of the final object. A modularity based on open and changeable designs will allow both architects and engineers to improve and to adapt the components continuously. A modular structure will allow components and modules to be exchanged by upgraded versions, new features to be added and, if necessary, modules from old building could be simply be refurbished using industrial processes.

In order to rationalize the building process within an adaptive modularity paradigm, it will becomes extremely important to identify all components that can be produced on demand with flexible and likely CAM integrated production processes, from others that must respect dimensional constraints because of more rigid production processes like casting or forming. A choice of the mix of these components must be done at the initial stage of design and this choice will influence the future possibilities of adaptation of the whole building system.
4 Learning from the Automotive Industry

Architecture can be considered a branch of design focusing on living spaces. The difference between houses and other objects like automobiles is that while automobiles are decontextualized, architecture is inevitably contextualized because of its link with the territory. This difference is a fundamental one and creates obvious problems in connecting ideas and concepts from one field to another. The questions of the relativity of fashion, the cultural legacy and the relations with the natural and built environment are all important issues for the architect. Nonetheless, it is important and necessary to look at other disciplines because the essence of effective principles can often be transferred.

4.1 Platform Systems

An interesting concept very diffused in the automotive industry is the idea of platform. This solution is shared by other industries like the computer industry, but it is in the automotive industry that these principles are especially easy to understand. A platform is the idea of having a common product architecture, sharing the same components and thus reducing the repetition of basic design and engineering work. In doing so, all the efforts can be allocated on design optimization and increased performance. This last point is essential: a platform strategy not only reduces costs, but also has the potential to increase overall value.

From another point of view, a platform strategy means mixing low volume differentiated components with high volume standardized ones. Reading this definition the whole idea of platform seems the application of simple common sense. Nonetheless, is worth noting that almost all objects surrounding us were not produced this way. There is a variety of reasons for this: market segmentation and diversification, product evolution, differing designs and probably the most fundamental of all: the non-cooperation between market competitors.

Can the construction industry use this concept? Can independent prefabricated systems share a common platform with elements and components sharing the same basic design principles and interfaces? The construction industry operates on an extremely diversified product, is highly fragmented and it is traditionally local. These are all conditions that are limiting the benefits of the traditional standardization achieved by strong modularity, limited options and at the end the perception of a less sophisticated product. If some of the many builders of prefabricated building systems would work together on the creation of a common platform the situation would likely change.
In the automotive industry, standardized components like chassis and suspensions save manufacturing costs when the production relies on important fixed costs. In a logic of compatible interfaces, more important than the size of the elements will be the fundamental logic of their assemblies.

Within a general guideline limiting the welded connections, in a steel framed building, it will be of fundamental importance to know the exact design logic governing the bolted connections. This means that proportions, distances and dimensions must be exactly defined in an algorithmic way. The idea of associativeness introduced in the previous chapter may provide an intuitive tool for achieving such a system of coherencies. These are all questions that may be of secondary importance in a traditional architectural design, but are fundamental in an approach based on a shared platform.

4.2 Open Building Systems
The high need of customization has always been a limiting factor for prefabrication. An open building system, representing a theoretical platform and available to everyone, has been considered by many as a solution.

There has been a good deal of research in this direction, but so far the impact has been minimal. A research project partially funded by the European Union and led by a consortium called ManuBuild, was funded with almost 20 mln Euros with the idea to create an open building manufacturing system. This project was promising “a step change from current modern methods of construction towards an era of inspirational, unconstrained design with ultra-efficient manufacture and industrial-style construction”\(^6\). The project ended in 2009 with a series of publications and since then it almost disappeared.

Looking at the material produced by this consortium there are a few facts that supposedly lead to this failure. First, the focus, because of the very technical exposition of the concepts, was mostly on engineers and industry managers. Second, the ideas exposed were always case specific and always leading to a strong standardization of shapes, dimensions and components.

Forgetting about architects and designers is missing the opportunity for a change. Architects, even if sometimes acting as outsiders, are the first and most defining subjects in the construction industry. Concepts that can be used only down the production chain, leads to theoretical solutions that

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\(^6\)http://www.iaarc.org/publications/proceedings_of_the_23rd_isarc/the_integrated_project_manubuild_of_the_eu.html ((accessed December 2015))
will be never used in practice. What is necessary is a system where design and production tools are fully integrated.

What does a platform for the construction industry should look like? Such a platform should be a building system sharing the same inner coherence from conception to production. The focus should be on the rationalization, not of the design, but of the design principles. Construction is a product with a scale large enough to allow on demand fabrication. The problem is not using the same grid with the same size but finding an agreement on the generating rules. Two architectures can share a design generated by the same sequence of operations and at the same being two formally distinct objects. This possibility will be better explained in the following chapter.
5 Parametric modelling

Parametric modelling is not new. We can find traces of parametric thinking already in the antiquity, with Vitruvius describing buildings and war machinery with ratios and equations. In a less strict version, variations on a given typology have been the driving engine of the city’s development for centuries. Today, walking in the old towns all across the globe, we all recognize the pleasant feeling of this variable repetition.

Looking at the recent history, parametric ideas in digital design were already an essential feature in Sketchpad, the first ever CAD program issued in 1962. By the end of the 80s, 3-D parametrically based software like Pro/Engineer or CATIA already achieved a good commercial presence and became a standard in industries such as aerospace, naval engineering or car manufacturing. For a set of reasons ranging from the simple resistance to change to costs and the fact that the initial versions of this software were not extremely user friendly, the construction industry preferred to implement 2-D CAD systems and kept 3-D at the margins.

There is a common misconception about parametric modelling. Most critical views focus on the risks of automating the design process leaving all creative choices to the machine. While it is true that parametric systems are considered by computer science the most primitive stage of artificial intelligence, it is clear that in a parametric environment, a programmer is still the central actor. A design may not be modified anymore by directly deleting and replacing a line, but the structure behind this design is still the work of the creator’s mind.

Design is an iterative process. What parametric modelling really does is to empower the designer to work with greater flexibility and potentially speed. The architect usually starts with the required client’s requested
program and combines it with his own general vision. Once this vision is better defined, the designer starts working on the elements, structural or formal, that will allow such a vision to be built in real life. These elements and the vision as a whole must be adapted iteratively and this can be a very tedious job, especially when these elements must be replaced manually and every iteration requires hours of work. This iterative process can be done manually or, using parametric design, computationally. If the soundness of a project remains unchanged, there is no clear advantage in doing all the iterative work manually. No only so, computationally made iterations guarantee at any point in time the coherence of the whole set of plans, leaving no room for errors. Problems may arise but they can be immediately identified, fixed and the solution will spread automatically everywhere at every scale.

5.1 Meta-Design
We established the supremacy on this plant through the development of tools. The initial tools were simple material extensions of the body but the real turning point was the invention of another kind of tool: language. This new body’s extension enabled human beings to work together both flexibly and in large numbers and leaded to an explosion of innovation. The digital revolution we are experiencing today is just a stage of a very long development of instruments that, like language, are not tools themselves, but are catalysts of innovation and creativity.

Philosophical speculation is not the aim of this short essay, but considering the computer just as a digital pencil or a digital 3-D model maker is like using language just for screaming. Computers can be used as a simple tools enhancing productivity (like typing on a word processor), but the real potential lies in their ability to embed knowledge and to systematically transform this knowledge in what we specifically need. During the last decade, digital tools have been extensively used in the architectural profession, nonetheless the use of computers has been mostly confined to simple graphical tools.

Donald Knuth, Metafont description language, 2014
So, what is meta-design? Meta-design is, simply put, the design of the design. This task, which has always been theoretically possible, but limited in some cases by the computational requirements, can today easily be accomplished using the available mass produced digital tools.

Meta-design is the higher-level of understanding of a problem and therefore the generation of higher-level solutions. The word higher is not used in a qualitative way, it simply defines a more general approach with broader perspective. Meta-design is more about defining principles than specific steps and requires both a filter and a formal rationalization. The advantage of creating a design tool instead of a simple design, is that solutions can be transferred from one field to another without losing their effectiveness. Solutions developed this way are adaptable and not brittle. Developing solutions at this level requires skill-based knowledge that, unlike fact-based knowledge, can only be acquired through practice and direct experimentation. Consequently, meta-design not only is capable of an effectiveness of one or two orders of magnitude higher than simple design, it uses extensively the designer’s distinctive mental patterns and experience and as a result it is the direct expression of the human intellect.

5.2 Associative Design

“Associativeness is the principle used in software that organizes the architectural project in a long chain of relationships, from the first conceptual ideas to the driving of the machines that will prefabricate the components to be assembled on site”. Bernard Cache, Projectiles, 2011
Associative design is the abstract, meta-design version of the conventional design process and a whole object can be synthetized in a set of formal operations. Two architectures can share this way the same sequence of formal operations, but through the variation of parameters and geometrical relationships their final appearance can be very different. In the construction industry, where most components are produced on demand and do not require high fixed production costs, it would be feasible to create, through digital fabrication, adapted components sharing the same underlying logic and it would be possible to create this way adaptable architectures.

It is necessary to deepen the question of variation. Associative modelling may lead to designs that from the outside look identical at forms designed with freeform modelling. Nonetheless, the difference between the two methodologies is fundamental. Freeform shapes can be modified by control points, but these control points are not managed by and exterior set of rules, therefore, any variation will be a random occurrence. Associative modelling, on the contrary, follows a strict set of rules that guarantee the reproducibility of the variation at any scale and sub-scale of the model. Associativity is able to crate shapes and structures that share the same logic but can be adapted systematically to different configurations.

That said, it is important to underline the fact that associative modelling cannot be a general design tool. Since it pushes the designer to think at the project in a rational and organized way, defining all the important underlying hypothesis in advance, at the early stages it is probably better to rely on simple sketches or ordinary CAD software. However, once the design is more or less on focus, associative modelling becomes a powerful tool enabling a synthesis of the proposed ideas.

5.2.1 Bottom-Up Design

The way the chain of relationships is modelled between the geometries and the elements may vary depending on the flexibility of those elements and the behaviour we want the final design to express.

The most simple method is the bottom-up design which consists of creating parts independently and then assembling them together using positioning constraints. This method is the most diffused in prefabricated design and has several advantages. It allows individual parts to be specified and modified independently and it allows an easy collaborative workflow where different people can work on different parts at the same time. The disadvantage is the impossibility to express a general adaptive behaviour.
5.2.2 Top-Down Design
This method consists of working within a predefined assembly and creating parts directly in it using the geometry of the neighbouring parts. The top-down design method is subdivided into two different methods: associative top-down design and non-associative top-down design. The difference is that in associative top-down design a change in the geometry of reference will update the inserted geometry while in the non-associative top-down design the inserted geometry will keep its initial shape. There are advantages and disadvantage in both methods, it’s really a matter or experience and the specific situation. If the inserted part cannot be produced on demand, non-associative approach is probably the right methodology, otherwise it is probably better to keep a complete system of coherences.

5.2.3 Hybrid Design
This method tries to combine the advantages of both previous methods. The chosen mix between top-down and bottom-up design may lead to a design with the same appearance but with a very different underlying structure. It all depends on the initial conditions and the generalization the final model must reach.

Looking at the typical architectural conception, contemporary practices probably privileges the notion of and wholeness related to an initial vision. Other schools in the past were working mostly on an idea of composition and especially starting from the industrial revolution, there have been experiments trying to create objects starting from structural principles. Still, at the end, all these different design methods lead to an iterative process that relies on what is de facto and hybrid approach.

The attention given to the explanation of the different methodologies may seem redundant, but associativeness relies first and foremost on a formal rationalization and different approaches will determine distinct outcomes.

5.3 From Conception to Production
Ideally, there should be a continuous between design and manufacturing. Without this condition, most of the productivity gains achieved with parametric and associative modelling simply disappear because the added handling layer.

Not only so, the idea of associativity itself is compromised. Unlinking design from manufacturing creates difficulties in iterating between the desired design and its adaptation to manufacturing possibilities and conditions. This loss of control prevents the designer from applying the necessary corrections, rationalizations or improvements and gives to the manufacturer an important margin of decision. The idea that the manufacturer enters into what is a design domain is not a bad thing in
itself, being the manufacturer the holder of important field specific knowledge this could be highly beneficial. However, problems may arise when the interests of the designer and manufacturer are not aligned, or when a lack of coordination results in suboptimal choices and outcomes.

Without an integrated sequence starting from conception to manufacturing, it is difficult or impossible for designers to understand quantitatively the impact of nonstandard choices of details and shapes into their projects. This integration was difficult in the past because of the field specific knowledge it required and the lack of tools capable of linking design to manufacturing. Modern digital tools have the potential of making this integration much easier.

It is worth stressing that the nature of the construction industry, with its fragmentation and its procurement systems, makes a real vertical integration very difficult. At the same time, because of this very reason, the benefits could be enormous. In the manufacturing industry, the integration of processes and feedbacks from production to design are a common practice and the difference in quality and productivity is under everybody’s eyes. This is especially true if we consider that most of the improvements achieved by the construction industry come from products originated through this kind of processes.

5.4 Adaptive Building Systems
Every manufacturing method is scale dependent and this is one of the main arguments used for justifying the limited industrialization of the construction industry. Architecture is always built from components, both directly or indirectly like in the case of casted concrete. Processes creating

Snohetta, Norwegian Wild Reindeer Pavilion, Hjerkinn, 2011
the final object from homogeneous materials work, with few exceptions, only on the scale of a model.

The main challenge is therefore the integration of discrete and heterogeneous parts into the final form. This challenge is especially difficult when the conception brakes the usual orthogonal grid and the desired shape is designed on a theoretical continuous.

Building systems available today are standardized in a way that their components impose their form to the final object. Without the possibility to rely on building systems with the ability to adapt, every experimentation of form will end up with costs overruns or with simplifications killing the initial idea. In order to open architecture to novel typologies and their variations, this experimentation must be done in a cost-effective way.

This goal can be reached with the development of a different kind of building system. The progress from industrial age to information age provides the necessary tools. With computer numerically controlled manufacturing equipment there is little difference between fabricating a hundred similar or a hundred different parts. Building systems may therefore become adaptive, following the shape of the building instead of forcing the building to fit the system. Such adaptive building systems can consist of few parametrized components that can be combined in order to attain the final desired result.

The possibility to produce identical or distinct parts with no impact on the production costs does not mean that there are no economies of scale in the process. With integrated CAD/CAM systems, the economies of scales that in the past could only be obtained on the production side of the process, are now linked to the development cost of the adaptive system. This cost, considering the scale of the typical architectural object, is likely to represent a small fraction of the construction budget and therefore seems a sound investment. With such a workflow in place, building systems will no longer define the form and the structure of the building, it will be the geometry and the structural requirements of the building to define systems and components.

5.4 Associativity for the residential sector
In residential objects is necessary to work with very limiting site constraints. In customized designs, these constraints are usually handled manually but a system that could adapt seamlessly would make the process much easier and consequently more efficient.

Until now, the attention was mostly put on formal considerations but, as exposed earlier, digital tools have the ability to offer general solutions to general problems. Parametric associativity can be used not only for formal experimentations, but also as a guide for performing better choices in
terms of costs, allowing the allocation of financial resources where the marginal benefit will be higher. The ease to produce variations, enables the possibility of evaluating different alternatives and finding the best constructive option quantifying immediately the impact on costs.

Increased spans are related to the weight and the cost not only of the horizontal profiles but also of the supporting columns. The choice of the profiles often imposes a trade-off between weight (and therefore cost) and structural depths. These constructive choices are usually made by the architect and heuristically corrected by the engineer. While it is true that there is always the possibility to rely on previous works and to the acquired knowledge and experience, many of these relationships are not linear and even the optimization of a simple structure can be quite complex. Digital technologies are capable of managing this complexity and therefore their integrated use will benefit every stakeholder in the project.
6 Case study

In order to show the concepts developed in this essay, we look at a project built in 2004. The purpose is to understand the constraints of a real case scenario and to assess if a parametric and associative approach could have made a substantial difference in both design and manufacturing.

The chosen project are the noise barriers in Chiasso, designed by Arch. Mario Botta, engineered by Grignoli Muttoni Partner SA and manufactured by Officine Ghidoni SA. The barriers are characterized by an unusual tree design. This kind of branching structures were already conceptualized by Frei Otto in the 60s and realized probably for the first time in the 80s for the Stuttgart airport. In the case of Chiasso the structural system is intuitive and it doesn’t represent an innovation in itself. On the contrary, the casted nodes were a solution never seen in Switzerland before.

This case study is an interesting one, because it allows to dig into a free form paradigm which is unusually strictly functional. The geometry that may seem regular and repetitive at a first look is in reality potentially quite complex because every element must to fit into the curvature and the slope of the road. As a result, every element must be positioned in the space on plans that are not orthogonal and this condition generates geometrical problems difficult to handle.
6.1 Original Designing Process
The project was originally designed on a 3-D software (Bocad Steel). The software was quite advanced in terms of details conception and automatized documentation. Nonetheless, a major problem was that there was no geometric modelling kernel and therefore most of the geometry had to be inferred manually. There were 64 modules to fit into the site geometry defined by hundreds of measuring points. The study of the geometry, the detailing and the production of the necessary documentation, required some 2000 hours of work.

An important part of the work went into finding the best way to simplify the geometry in order to decrease the manufacturing costs. In the steel workshop there were CNC machines but no integrated processes. The standardization of the tree module was therefore necessary in order to fabricate the project cost-effectively.

Looking at the executive plans, it is necessary to say that most geometrical problems were solved simply by ignoring them. This was possible thanks to the very gentle slope of the road (around 1%) and the very smooth and regular curvature (ranging from 0.17° to 0.27° between every module). These simplifications were rational and impacted only very slightly on the whole appearance.

*The welding of the main branches was done on site using a changeable template.*
More than on relying on the study of a perfect geometry, the workshop focused on its experience. The knowledge gathered in decades spent on working sites, enabled the estimation of the real tolerances required for such a project. Later on this chapter, a geometrical precise version of these modules will be showed, but it’s necessary to understand that the conditions on site are not the ones on the screen. A light steel structure spanning on 15 meters, will require, no matter how precise the conceptual conception is, the possibility to on site corrections.

After studying the geometry of the road, the steel workshop concluded that the entire project could be handled with just 6 slightly different variations. The curvature of the road, being extremely limited, allowed the possibility to absorb the length differences between the front and the back just by adapting the two most external profiles, leaving therefore the core of the module practically unchanged. For the others small corrections, the structure relied on adjustable connections and on a 11cm space between each module.

The choice of modifying only the external profiles, leaving the geometry of the central parts unchanged, was driven by the fact that one of the key constraint of the project were the casted node elements. Since there was only one version of them, everything else had to be adapted consequently.

Another important choice was the assembly workflow. The roof was transported on site divided in four horizontal elements and extra tolerances in the bolted connection enabled some extra flexibility. The small difference of geometry in the main branches of the six different version of the tree, were handled using slightly different templates and welding the tubes directly on the node on site.
6.2 Parametric Associative Modelling

The project was redesigned in TopSolid, an integrated CAD/CAM software based on the geometric modeller ParaSolid. All digital files are available to download online\(^8\). The work was done remotely from home using the Virtual Desktop Infrastructure (VDI) provided by the CNPA Laboratory of the EPFL.

The internet is crowded of experiments in parametric design, but very few of them depict structures that can be translated into reality. Designing surfaces and conceptual structural elements is one thing, adding a thickness to these surfaces using the available profiles and components, with coplanarity and orientation constraints, is a problem of another level.

Creating digital free forms is nowadays extremely easy using the right CAD package, it simply requires a bit of experimentation and practice. The real challenge is therefore not to design a complex free form, but to design the fabricable version of it. Components come with given thicknesses, that once orthogonality is lost, create very intricate geometrical problems. Details must be integrated seamlessly in the geometry and an unknown number of exceptions must be handled developing general flexible rules.

It is possible to summarize the whole process in terms of discretization. While in the digital world the work is in an (apparent) continuous, in the real world, in order to build a shape, it is necessary to discretize it. In order to operate this discretization, many panelling tools and plugins are

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\(^8\) The digital files are available to download from the following link: http://www.matteopitton.com/adaptivesteel.zip
nowadays available, but most of them fail to solve the real construction problems. What they do is to output a somewhat complex geometry that can be used to visualize this discretization and can provide a reference. Turning this complex geometry into a real object requires many additional steps that a simple parametric approach cannot automate.

This discretization implies that approximation errors from the ideal shape and the manufactured shape are scattered all around. A good balance between the amount and the importance of these errors and the manufacturing complexity of the structure must be found. There is an exponential inverse relationship, where small initial adjustments can lead to big improvements, and then, the complexity required in order to achieve the next improvements becomes so overwhelming that it is not economically interesting to go further.

6.3 Design Hypothesis

Working with parametric associative modelling, the design process cannot start with a simple generic line. In order to be generalised, the object must be imagined in its wholeness and hypotheses must be applied in order to rationalize and formalize its form.

In the redesign of these steel structures, the basic guideline was to avoid an increase in the manufacturing steps. At the same time, the intention was to make good use of theoretical computer controlled production processes, in order to improving the components’ geometrical fit. As an example, the horizontal steel profiles, which are kept linear in the built version, are kept linear even in the generalised redesigned version.

All the complexity of the geometry is taken by the components that in any case would have required a computer controlled fabrication. If a component had to be cut in the real version with a simple unidirectional cut, it can now be cut with a more complicated double directional cut. The assumption is that, if a computer controlled machinery does this cut, the processing time and cost are same and therefore a better fit does not come with a costs increase.

In order to show the flexibility offered by this kind of modelling, the tree modules will be pushed into fitting a much more demanding geometry than the one present Chiasso.
6.3.1 Site Geometry
The first hypothesis is that, using an algorithmic process, the whole construction can be subdivided into coherent separate modules. The modules should follow a generic road, no matter if this road is on a plan or it freely develops into the space. This algorithmic process, in order to be completely automatized, would have required some scripting. Nonetheless, it could be partially automatized using the standard tools provided by the software. A choice was made to keep the later faces both coplanar and aligner to the $z$ axis.

The first step of the workflow consider creating a spline with 3-D points which could represent be the real measurement points on site.

The second step is the discretization of the continuous spline. The spline is subdivided with points divided by an absolute distance that can be parametrically chosen and a segmented line connecting these points is drawn. In order to define the right cutting plans, the 3-D segmented line is projected on the $xy$ plan and middle axes are created between every two segments. This is necessary because the references automatically generated from the spline would be perpendicular to the tangent of the spline and with a continuously changing curvature, this would not allow us to create coherent modules.
The third step is the creation of a section representing the volume occupied by the structure.

The fourth and last step is the creation of references linked to the points generated on the 3-D spline and oriented through the created middle axes and the z axis.

By inserting the measured coordinates from chiasso into the 3-D points defining the spline, we can easily infer the exact geometry of the real built project and we can experiment different widths of tree modules.
6.3.2 Modular Constraints
The second hypothesis is that the geometry of each one of these individual modules can be derived, following a long chain of operations, from just 8 control points that will “stick” to the site geometry.

In order to model the position of these 8 generic points in the space, a geometrical frame is built having the only constraints of coplanar lateral faces. Height points are then placed to each vertex. It would be theoretically possible to work with 8 abstract points put randomly in the space, but this would make impossible to visually understand the next operations and it would potentially cause geometrical issues in defining geometrical constraints and references. The possibility to visually handle the geometry is a big advantage compared to purely algorithmic approaches.

Once these first 8 points are inserted, a volume defined by the coordinates of these points can be created. The next step is the insertion of an initial structuring system based on middle points and orthogonality. This orthogonality is the key for keeping the geometry in line with the principle of not adding manufacturing steps.
6.3.3 Design Formalization

The tree tubular structure and the roof curvature, had to be modelled thinking at a general geometry, which could be intuitively used without introducing to much complexity into the controls. Imagining the process that Arch. Botta could have been trough the design and knowing that he usually works with pure geometrical shapes, the idea was to include the tree on a circle and its equally spaced rays. Every parameter can be adapted and an unlimited set of variations is possible.
6.3.4 Generalization Through a System of Coordinates

Using a system of coordinates instead of a geometry composed by segments allows a much greater flexibility. The coordinates are generated by parametric repetitions based on axes and planes coming by the geometrical integration of the general volume and 2-D tree sketch.
6.3.5 Dressing and Insertion of Standard Profiles

Once the system of coordinates is defined, standardized steel profiles are put in place and all the limitations and orientations are done automatically. Thanks to the generalization of the geometry, the steel tree is able to adapt in every dimension keeping a strict coherence in every construction detail.

The number of members composing the roof can be changed parametrically (in the example from 13 to 11).

Adaptability to the slope

Adaptability to irregular curvatures
6.3.6 Insertion of the Adaptive Modules
In order to create variations driven by the 8 control points that define the whole tree structure, a generic family is derived from the mother assembly. The 8 “sticky” points can be visually chosen from the site subdivision previously made. This operation allows to place every module precisely into the site constraints. Once the modules are in place, their design can be still modified changing the settings of the mother assembly.

The site constrain defined by the 3-D spline can be dynamically updated. Unfortunately, because of the limits of the shared VDI, it’s not possible to insert more than a dozen modules together or the system will become unstable. The structure may seem not excessively complex, but the hidden operations enabling its adaptability require a huge computational effort and most of all a great amount of allocated memory.
An important feature of the model is the possibility to work on the constraints defining the geometry of the tubular structure. This is of paramount importance, since the casted nodes are standardised elements and they will not accept changes in the inserted geometry.

It is important to underline the fact that the geometry of tree structure is not simply scaled or morphed, all relationships remain the same, what happens is simply a general adaptation. A bill of materials can be printed out, if necessary workshop plans can be automatically generated and most of all, the instructions for fabricating each and every element can be directly sent to the workshop where a CAM process can make them reality.

The model was developed in order to adapt at the 3-D geometry of a generic road within the limits of the original design. At the moment the model can be adjusted very precisely but only under certain limits. Enabling bigger generic changes in appearance would have required a further generalization.
In any case, it is possible to claim that it was possible to transform a geometrically demanding architectural infrastructural work, into a product that can be potentially used everywhere.

6.4 Assessment
In the previous chapters, the possibility of using a parametric-associative approach for generating adaptive modules was discussed. A broader concept of modularity was introduced where the modules could be composed by more than one element. The condition was that these elements had to remain coherent. This case study show that such an approach is feasible.

The work on the geometrical constraints and the generalization of the geometry was not an easy task. The time spent in modelling is difficult to assess since I started practically as a beginner and many hours just flew away playing around. Nonetheless, once I started to understand the inner logic of the system it took me around 100 hours to achieve this result.

I can conservatively assume that a trained designer who already solved similar design problems can accomplish what I did in no more than 20 hours. This is a great feature of this approach, not only the design tool allows a great increase in productivity, but it also it engages into important economies of learning.

The level of detail achieved is not at an executive level, but once the geometry is in place, this additional layer is possible. There are two problems linked to the detailing. The first is related to the increased complexity of the model and therefore the computational power required to handle all additional geometric constraints. The second and the most
important, is that details are very difficult to generalize and they would require a good investment in terms of modelling time.

In this essay, Building Information Modelling (BIM) has never been mentioned because it would have opened an extensive parallel discussion. However, the link with the work just done is straightforward. The complete digitalisation of the construction design and the possibility to have at any moment a synchronized documentation would have easily enabled a BIM methodology. The flow of information would have reached directly every participant in the project and the erection of the project would have been surely much easier. As a side note, we can mention that, in fact, a BIM methodology would have had a tangible impact on this project. The company in charge for the production of the glass elements of the roof used a wrong construction plan and delivered more than 1000 wrong glass plates (these plates were stratified and temperated and therefore almost impossible to recycle in other projects). This caused delays, legal consequences and for the supplier it meant a huge loss.
7 Conclusions

Writing about construction, steel and manufacturing processes without a direct experience and relying mostly on second-hand information is obviously a risky exercise. However, looking at things naively gives the possibility to put questions to things that are usually taken for granted.

The steel construction industry can benefit tremendously from a shift of paradigm allowing fully integrated digital conception and manufacturing. An adaptive steel construction can be developed and the logical application of this new possibility seems to be the residential sector, a domain where the need of customization and variety is much greater than in commercial and administrative buildings.

Designing parametrically and associatively is an exercise for logical and clear thought. The ability to sequencing the operations leading to the creation of the wanted object, not only produces a clearer design capable of speaking for itself, it also enables this design to be easily generalized, used and improved by others.

Creating a design in a formally beautiful way using the minimum possible information is not an end in itself: it allows grasping its real essence and by doing so, it creates the possibility for this design to be used in different fields and circumstances. The handling of geometrical constraints used for a wooden shelf can be used directly for solving the design problems of a rooftop, allowing this way an otherwise difficult cross-contamination of solutions between different programs and scales.

Automation in design is as important as automation in the manufacturing processes. Everything surrounding us had to be designed in first place. The possibility to focus on the conception removing all repetitive tasks is the real innovation brought by digital technologies. The possibilities offered by digital processes are still far from being completely understood. The concept of associativity can turn into reality a system of adaptive standardization where variation or repetition will just be a matter of choice. This revolution in the way we design the space and the objects around us, could lead to enormous improvements in terms of productivity in a world hungry for good design.

Nowadays we have powerful design and manufacturing tools that are not used at their full potential. One of the reasons for this situation is that these tools are seldom used together. On one hand, we limit the outputs generated by our design processes because, without integration, they would be in any case too complex to manufacture. On the other hand, the sophisticated computer controlled machinery available in our workshops, perform mostly repetitive tasks because the inputs they receive is filtered
by manually generated designs that cannot handle too much complexity. If there is a concept to retain, it is the one concept of integration.

There is a huge amount of talent within the design profession. Unfortunately, this talent remains most of the time frozen into beautifully crafted digital paintings we all call projects. Design is the first signal of human intention, being able to put in place a beautiful process leading to a smart design should be as important as the look of the final unique object.
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