The Sagrada Família:  
The Starting Point of CAD/CAM in Architecture

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Abstract—There is no doubt that technology is a trend affecting almost all professional fields including architecture. Within this movement, a series of innovative strategies has emerged. Among them, and probably one of the most affecting systems which links computer design to construction, is the Computer Aided Manufacturing (CAM).

In order to reach to the roots of the beginnings of application of CAM technology in architecture, one of the most important and unfinished projects designed by Antoni Gaudí, the Basilica of the Sagrada Família in Barcelona, Spain, will be taken into consideration. This masterpiece, defined as a challenging work of great geometrical complexity, started in 1882 and has been always short of tools to be built, thus proving that Gaudí was an architect ahead of his time. It has been noticed since the beginning that non-conventional ways of designing and building had to be applied. As a result a very slow development of the project on site was appreciated. Once the design process was rationalized, the challenging amount of data needed to be translated to workers on site in order to execute a specific component was high and human resources were noticed not to be sufficient.

By introducing high tech tools, both software and hardware, the process of designing and building of the Sagrada Família is becoming more dynamic, keeping the reliability of Gaudí’s design principles, and a faster, optimized and totally consistent product which comes directly from the designers’ parameters and guidelines. With the help of high tech systems, it was possible to optimize time and material in construction, in addition to defining a series of options for components before approval, with the aesthetic precision needed to be followed in order to comply with Gaudí’s principles. With such a system, it was possible to build an architectural component fully automated in the early 1990s, being this fact not just a total success, but an unprecedented way to build architecture with the help of high tech tools.

Keywords—Architecture; Antoni Gaudí; Sagrada Família; Technology; CAM

I. INTRODUCTION

Nowadays we are quite familiar with projects of complex forms as technology is allowing us to design and control them in such a way that we can respect the architectural principles of design such as aesthetics, functionality, and structural consistency, among others. But before advanced design and construction systems became popular, an architectural revolution and adaptation of such ideologies has happened. And even before that, a series of experimentations were supposed to take place in order to find the proper way to integrate architecture and technology.

For instance, in the field of design, robots are allowing us to do almost everything we want. For example, and arguably, any designer can draw anything and send it to a 3D printer right next to his laptop. This is positively affecting creativity and allowing us to appreciate the physical result of the design by using a tool which is becoming hugely popular. The same goes for CNC machines and robots, which if given the right task, can do almost anything. This is contaminating many professional fields related to design including architecture. But how are these high tech tools helping in the construction of something, which is considered by many as a masterpiece, conceived more than 130 years ago?

The Basilica of the Sagrada Família, “Fig. 1”, located in Barcelona, Spain, is an architectural work of art based on forms mainly inspired by nature and whose idea was conceived in 1883 by Antoni Gaudí, one of the most innovative architects of his time. Modifying the project initially entrusted to Francesc Villar Palau in 1882, Gaudí was aware that the change in the project and the radicalism of thoughts would involve documenting it with the maximum possible amount of detail. Villar had proposed to the Sagrada Família a neo-Gothic church of Latin cross of three naves, with a large crypt under the apse, a dome that reached the outside about 80 meters high, and a tower at the main entrance of approximately 100 meters height. Gaudí transformed, according to the actual chief architect of the project, Jordi Faulí, “the first neo gothic project from Villar into another of a personal architecture never seen.” [1]

In a personal conversation with Antoni Gaudí in 1902, Buenaventura Conill writes that the creator of this great work believed that the basilica of the Sagrada Família would need to be “an offspring of a long time, the longer the better,” keeping the spirit of the monument and depending on “the generations that transmit, live and incarnate.” [2]
Among the various well-defined projects that Antoni Gaudí left is the model central nave at scale 1:10 “Fig. 3”. This design is supported by a series of columns of a "new order" in which he has worked hard to reach a comprehensive solution. [4] These have been years of effort from Gaudí devoted to the study of a design which would surpass the classic style that over the centuries shaped architecture. [3]

The columns of the central nave in the Sagrada Família have a peculiar history. They are forms geometrically designed in a special way which could not be built until the late 1980s, and with an unsuccessful trial between 1954 and 1956 due to its misinterpretation of the geometrical transitions height. In principle, Antoni Gaudí had left well defined columns for the subsequent construction. [5] However, after his death, and then during the civil war, the chief architect of the construction of the church Francesc Quintana took the challenge of building the first column of the temple “Fig. 4”, known as the "column of Barcelona". [6] However, built with great difficulty, and in accordance with the chief architect in charge of the construction of the Sagrada Família from 1987 till 2012, Jordi Bonet, the component had not been resolved geometrically. [7] Bonet says that the collaborators of Gaudí "knew the task to be performed, but were not aware of the whole process." [3]
According to Jordi Bonet, Antoni Gaudí wanted to innovate with the formal appearance of the structure in the Sagrada Família by proposing helical columns of double twist. The design principle was based on polygons, defined as the hexagon and octagon, inscribed in parabolas rounding the corners or vertices of each point of the star “Fig. 5”. The Solomonic column could be obtained from this base with a “sweeping” movement, encompassing the helix to the right. As the next step, another Solomonic column is composed from the same base, having the helix turned left.

When these movements are arranged in a progressive multiplication of edges, the rotation is affected each time in a decreasing height “Fig. 6”. So, from horizontal transitions of one meter high, and with the aid of templates, Antoni Gaudí built with plaster models at 1:10 scale, with intersecting surfaces meeting when turning, according to the number of sides of the polygon, and always turning the same polygon.

II. HIGH TECH TOOLS FOR THE HISTORY OF THE SAGRADA FAMILIA

Antoni Gaudí had a great appreciation for technology, similar to Le Corbusier, one of the architects who perhaps tried to link man to machines at his time and whose fascination to this issue, according to Elisabeth Darling, was something decisive in his character and later fame. [8] Le Corbusier tried to express the new trend of modernism through his architecture and the use of materials such as concrete, glass and steel. This was something that was illustrated and defined in accordance with "the twentieth century as the age of the machine, dominated by technology and mass production." [9] But what Gaudí needed was far from being achieved at the level of technological advances of the time. There was a great need to create manual ingenious tools and trust their reliability, despite the huge consumption of time for many years. [3]

With the ambition of concretizing what Gaudí had conceived, innovative ways to transform geometrical principles to design and later to architecture had to be developed. In this line of thinking, two main branches were created in the technical office of the Sagrada Familia with the intention of playing a key role in effectiveness. Computer Aided Design (CAD) and Computer Aided Manufacturing (CAM) were systems being developed in order to help industries such as the aerospace or the automobilist, rather than architecture. Created
in different timeframes, and adapted by architects in a much later stage, they are both technological innovations that can be considered as the tools helping finishing Gaudí’s masterpiece.

With the increased popularity of CAD systems in the market, Mark Burry appears in 1979 to join the technological age in the church of the Sagrada Familia with its previous concerns, and later with his knowledge and interventions to a highly advanced CAD level, performing the first study of the church through the computer. [3] His role in research began with the drawing of a window of the central nave left by Antoni Gaudí, and his research advances led us today to the use of parametric systems to work with geometric interpretations that contrast with Gaudí’s formal principles to be validated as faithfully as possible before being built. [10]

One of the most important facts that have revolutionized the construction of the Sagrada Familia has a direct relation with high tech tools. Numerical Control technology (NC) was in principle a challenge that would require a new kind of dialogue in construction in addition to its already complicated formal challenges “Fig. 7”. The use of alphanumeric codes combined with the in depth formal study of components at the project by the architect made it possible to understand the behavior of a machine capable of such precise movement which generated the possibility of experiencing computer assisted construction for the first time in the work site of the Basilica in November 1989 “Fig. 8”. Starting this year, a new language was incorporated into the construction process of the work of Antoni Gaudí. These new terms would be part of the different steps to meet the requirements for the construction of the double twisted columns using NC manufacturing in the first stage of implementation of CAM technologies, where later many more design elements would be translated into physical components directly from the computer.

Jordi Bonet, along with his technical team, was the one responsible at that time to get this result, which can be regarded as an important architectural achievement. They were immersed in between two worlds that hitherto were unknown challenges for the architects involved in the construction of the Sagrada Familia.

By rationalizing Gaudí’s geometry interpreted by Jordi Bonet between 1987 and 1988, it was possible to draw and describe the interior columns of the Sagrada Familia in the format of mathematical operations. This data would result in the helical double twisted columns transformed into alphanumeric data which would later be transformed into a physical component. The first architectural element at the basilica built by using such technology, the “column of Lleida”, would be fabricated in the form of stone cut non-conventional components. The first piece to be machined was in early November 1989, the first stones placed in-situ in November 1990, and its full completion presented in January 1991 “Fig. 9”.

Fig. 7. Van Voorden Sigma 4, the first numerically controlled machine acquired by the Sagrada Familia in 1988
(Photo from archive of the Sagrada Familia)

Fig. 8. The Column of Lleida in the process of fabrication and approval published in January 1990
(Photo from the magazine El Temple)
During the same period, Frank Gehry also succeeded along with James Glynmph regarding the use of CAD / CAM for the construction of the sculpture for the Olympic Games in Barcelona in 1992, along with the use of a CNC machine for cutting stone components for the facades of the American Center in Paris “Fig. 10”, and the Walt Disney Concert Hall in Los Angeles at the end of 1991.[11] In the temple of the Sagrada Familia the "column of Lleida" was considered to be the symbol of a new possibility of help from computer numerically controlled technology, a not well recognized achievement in the history of architecture linked to CAM. Certainly, the achievements of Gehry from Barcelona have contaminated the digital architectural discourse and have prompted many architects to develop new lines of research in design and construction, perhaps with other methodologies, but with the same intentions, which is to make use of Computer Assisted Manufacturing Technology for the service of architecture. And this is something that is promoted in the temple of the Sagrada Familia since 1989, with the first stone built with a numerical control machine and the presentation of the first architectural component of geometric complexity, in this case of double helical twist, fully produced robotically in January 1991.

The architects involved in the construction of this great work had the opportunity to contemplate thereafter greater consistency and with a guarantee of success. Communication between information technology and the machines have been set to be, and remain until today, completely faithful to the process. Thanks to the consistent interpretation of Antoni Gaudí’s principles in addition of technology’s application, it was possible to achieve the construction of any component to perfection. Architecture responded to the utility and this was the reason why technology has been introduced in the Sagrada Familia.

CAM technology is considered a tool which has been used as a bridge providing communication between information and final components. Sketches of Antoni Gaudí, which were partly burned and destroyed during the Spanish civil war, and plaster models of the many parts of the building, especially the central nave, were rescued by Jordi Bonet as a reinterpretation of numeric data relating to the generation of the components of the church, and precisely built with the help of high tech machines in order to transform the great challenge of the creator of the Sagrada Familia into reality, which was based on achieving the new order. The achievement of the construction of the "column of Lleida" was not only the first double twist column to be built, but it was the first architectural
element of a unique geometrical complexity ever built in the world using NC technology.

III. HIGH TECH TOOLS FOR THE FUTURE OF THE SAGRADA FAMILIA

Subsequent experiments of the "column of Lleida" have shown that technology has been and remains a very useful tool helping in the construction of the Sagrada Familia. In addition, with the increased investment in technology, both in computer systems and robotics, the pace of construction increased significantly. The link within the technical office with this production process occurred very vigorously through research developments and strategies linking CAD and CAM media. Special forms needed special strategies to achieve first its production and then material optimization and time for manufacturing. The technical office of the Sagrada Familia had already reached accuracy back in the year 1989. Therefore, the aim has been since then and is until now to endeavor to optimize material and time. In addition, and as a result, this system is providing models and site workers aid to enable them to perform their work very effectively with real scale models, in addition to three-dimensional supporting elements, and bi-dimensional data.

Following the first numerical control machine acquired, the design and building staff at the Sagrada Familia increased their trust in technology. Machines have a tendency to employ manufacturing processes closest to industry than architecture, as it has been noted in the process of using the first NC machine in the church. Therefore, architects needed to apply mechanical application methodologies both at the program level and at the machinery and production strategies “Fig. 11”. It is required to employ background knowledge on the part of designers, workers and industry to find innovative solutions that first makes the production process more efficient and diversified, and then accelerate the process in order to optimize time. Saving production time would allow architects to further investigate the processes of design and would help in the creation of a greater number of proposals for a given component of the Sagrada Familia.

With the NC in 1989 and later the CAD/CAM in 2002, design consistency has been vigorously maintained in construction. Furthermore, a first level of success was achieved concerning time savings when fabricating geometrical components as extruded polystyrene models to produce negative molds which would be later placed on-site for the final construction of components.

Since late 2004, a major update was made by the Sagrada Familia in the field of CAD / CAM “Fig. 12”. With a team of specialized professionals, a wide structure in the technical office, new computers, software, last generation 3D printers, and new CNC machines and a robot, it has been possible to carry out various researches to reach the primary goals of Jordi Bonet regarding the implementation of robotic technology in the basilica of the Sagrada Familia taking into account accuracy, already attained in the early 1990s with the first numerically controlled machine, and economy in construction.

With today's technology, knowledge is used and processes are created so that both software and the machines are always working up to its capacity limits in order to give the desired results “Fig. 13”. The Sagrada Familia project is taking modern technology to its limits whenever digitally designing or physically concretizing a new component of Antoni Gaudí’s masterpiece. Therefore, technology is pushed to its maximum potential to concretize the challenge of building this spectacular work. Such a fact invites us to leave the door open to technology since the project is not over and it would be interesting to imagine, or even start to investigate, which technology would be useful to continue the great challenge to fulfill the dream of Antoni Gaudí and all those who have followed their ideologies, and for achieving the completion of this great work.

Fig. 11. Machines such as the saw disk numerically controlled machine acquired to execute copy of components of reduced scale (left), and the first prototype realized with the software CATIA and fabricated with a CNC machine in May 2002, linking totally the CAD/CAM process to the production of components at the Sagrada Familia de CAD/CAM (right)

(Photo from archive of the Sagrada Familia)

Fig. 12. Production process of a component which illustrates the process of transformation of digital data into a final component during the construction of the Sagrada Familia, passing through the stages of parametric design and fabrication, production and tools definition, molds and placing in situ

(Image from author)
With the help of veteran architects, mathematicians, and computer program experts, in addition to the great motivation and respect for Antoni Gaudi’s work, it was possible to achieve a great acceleration in the process of construction of the basilica of the Sagrada Familia. With some projects, among the many which has been and continue to be carried out, it has been possible to illustrate a complete process from design to the production of finished parts made of computer-assisted technology. Geometric principles were already defined, but thanks to computers, it is possible to draw and produce them in different ways “Fig. 14”. Geometric principles from Antoni Gaudi were defined and what was missing was actually deepening in concept thinking, trying to find the best architectural coherence, seeking a rational system of production and saving.

Fig. 13. Robot fabricating a stone component for the Passion Façade  
(Photo from archive of the Sagrada Familia)

Fig. 14. Three initial proposals for the central tower produced with 3D printers in 2006, where for the first time different formal solutions and their relations to the whole project were studied  
(Photo from archive of the Sagrada Familia)

IV. CONCLUSION

The balance between traditional and future technologies was found and placed in the service of the basilica of the Sagrada Familia in the 1990s. The consistent coordination between construction staff and architects opened up the possibility to new production strategies that would help accelerate the construction work. In manual construction, CAD was a staunch ally to provide addition to production, maintaining the fidelity of the drawings and the formal and geometric principles that were defined by Antoni Gaudi. CAM technology advances and its clearer link to CAD allowed not only new design systems, such as three-dimensional or parametric, but became a formal and rigorous principle of transformation from a series of visual relationships from a computer program on a screen to a physical component ready to be assembled on site.

The implementation of CAM technology and its current strategies studied for its continuation exemplify the difficulty of the challenge that Antoni Gaudi proposed us and thanks to technology and progress, today the construction of the basilica progresses more accurately, quickly and economically. Today, this technology is very appropriate but they are being taken to their limits and the project has not finished yet. How will the new and future technologies help to complete the construction of this work is yet to be known. The question is to ask what new practical instruments are needed to take advantage of the opportunities created by the modes of production that are applied in the Sagrada Familia.

This is a project that makes us rethink what happened between the 1950s and 1980s in relation to architecture and technology, where all tools were created. For example, one of the many basic tools of design such as Non-uniform rational b-splines (NURBS), computers and numerical control machines have been developed over the decades and used in many fields. It is true that such technology was unreachable for the architect until recently. However, architecture has incorporated this technology with some delay, and for example, could be speaking today in schools of architecture could relate their field with technology in a more advanced and natural way, and expose students to issues such as post-production, 3D printed models, or programs that serve as support tools in the process of design and construction with more awareness.

The balance between industrial technology and human resource has always existed in the Sagrada Familia, and even with high tech machines, this conformity continues to exist today. The machine did not replace the man in this project and will probably not replace it ever. Not for the reason that the machine could not, but human sensitivity expressed in art is not automated, although this factor could also be questioned. Technology has been and should always be a tool that is considered very useful in the construction of this work. For example, when defining construction techniques of molds and models for model makers, it is relatively easy to turn a milled element into a component for the manufacture of precast modules or to put them on-site to serve as a template or mold. Model makers have less work to generate the geometry manually because machines would be responsible for providing information or some of the information that would result in the
production of a physical element. It would be only a matter of time and applying the right manufacturing strategy so that the required component would be obtained.

Nevertheless, and looking ahead, it is questionable whether a project like the Sagrada Familia could be completely automated, although the sentimental values, through for example sculptures and handcrafts prevail. The machine, no matter how innovative it is, is actually nothing more than a tool in the service of man. However, and perhaps, a future machine with feelings that were able to create natural sculptures through digital means could one day revolutionize this concern.

REFERENCES