Chapter 8

Technological Advances in Design and Construction: Bridging the Gap between the Conception Stage and the Manufacturing *Process*

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Throughout all stages of civilization, tools have resulted from successive development, providing people with "essential freedom" (Jeanneret-Gris, 2007). Understanding the development of new tools sets the boundaries to what is possible and what is not. Whilst machine tools enables the production of objects that are exact copies of each other, hand tools enable creation of unique objects (Giedion, 2007).

As production tools have become mechanized products have become homogenized. In the course of industrialization, production tools have become mechanized; therefore the production of many objects now takes place in factories. Similarly, the production of a building, its component parts or units, have moved from taking place on-site to off-site, in a factory; this method of production is termed the "*prefabrication*". In which the component parts, units or modules of a building are manufactured somewhere else, then transferred to the construction site for the final assembly.

Prefabricate as its syllabuses *"pre"* and *"fabricate,"* suggest means construct or manufacture before in time and place. The particular circumstances of the 20th century being the development of new materials and new technologies (pluming, HVAC being heating, ventilation, and air-condition), urgent need for low cost lodging that could be constructed speedily, lack of specialist and local technicians, and the desire for a high standard and modern life in the wake of the war, made a ground for new approach to the design and construction of the house based on prefabrication.

Since its inception, the *prefabrication building industry* has operated without architectural guide (Davies, 2005). In his book *The Prefabricated Home*, Davies explores the links between prefabrication and the architectural profession. He by presenting examples like Le Corbusier''s machine-like Citrohan House, Frank Lloyd Wright's organic Usonian Houses, and

Buckminster Fuller''s aircraft-inspired Dymaxion and Wichita Houses, highlights not only how the modern architects embraced the machine aesthetic of industrial materials and production techniques but also how their visions and design have failed to be realized in the lack of economical concerns. Further Davies counterpoints these with commercial efforts such as AIROH, General Houses, Lustron, and Frameform, which have been more successful in the marketplace and eventually drive the production line.

A building, which is the product that results from the conversion of raw materials, was historically produced under basic activities of design together with engineering and construction. The limitations imposed by the machines used to fabricate components with a time constrain, have meant that the buildings produced by this industry have been simplified in both their construction and design. Parameters such as site characteristics, continuity and variation that are considered important by architects (Spuybroe, 2009) have not been the concern of the industry either. A gap has developed between architecture and building manufacture that can be interpreted as a rift between the act of conception of a building and its actual production. "Conception" is used in this paper to mean the action of forming an idea of the way a building will look, perform and mean.

Similar to machine tool the digital tool offers degree of freedom and affects the product it makes. The development of digital technologies has enabled many industries such as car manufacturers, aerospace and shipbuilding, to work around the limitations of machines. They have embraced the idea of integrating the conception of the product by designers into the manufacturing process. Their products, though highly complex, do have a variety of shapes and functions and performs perfectly in the environments in which they are used. A comprehensive study by Kieran and Timberlake (2004) of new materials, systems, assemblies and technologies used in such industries aimed to elevate architecture to a new level. At the same time, Woudhuysen and Abley (2004), whilst researching why construction methods appeared underdeveloped, argued that the construction industry has to embrace new technologies and manufacturing methods. Seeking better craftsmanship, quality and design, the two fields of architecture and manufacturing will face a regressive future if there is no change to their current design, supply and construction techniques (Wouldhuysen, Kieran, & Timberlake, 2010). Many noteworthy authors have studied the impact and evolution of the new technologies on the two disciplines. However, there have been very few authors, Kolarevic (2003a) being an example, who have described the new path that the conception and construction of prefabricated buildings might take by using the new digital technologies.

This paper will show the capability of these digital technologies, coupled with their increasing use within the architectural design world. Further it presents the vision of architectural profession of the future use of these new technologies and where those visions have failed to materialize. Finally, it will speculate on new directions in the prefabrication and how architects today are redefining the sustainable building of tomorrow. The aim is to reduce the gap between the conception and the realization of prefabricated buildings by giving a better understanding of the architectural profession way of using these tools to their counterpart profession. In this paper, I suggest that the building industry should embrace the production of more complex, asymmetric buildings than it currently produces, since current technologies allow the production of the complex and nonstandard building to be as economic as symmetrical one. Popularity of such prefabricated buildings had been because of the economic advantage (Armstrong, 2009) afforded to them by the use of machine tools, in respond to the needs and particular circumstances of 20th century. However as the needs, abilities and circumstance of contemporary society has changed this advantage may no longer exist.

Moving towards the Information Age

In the industrial age, machines enabled mass production. Current technology has brought variation to the products. As Kolarevic (2003a) noted: 'the Information Age, just like the Industrial Age before, is challenging not only how we design buildings, but also how we manufacture and construct them'. The development of tools at each stage of civilization produced products specific to that stage. The Crystal Palace, designed by Paxton in 1851 during the industrial age, reflects the characteristics of machine production while the Guggenheim Museum, designed by Gehry in 1997, reveals the characteristics of computer-controlled machine tools in the Information Age. As tools change, so their operation requires a different degree of physical and mental input from their human operators.

From Hand Tools to Machines

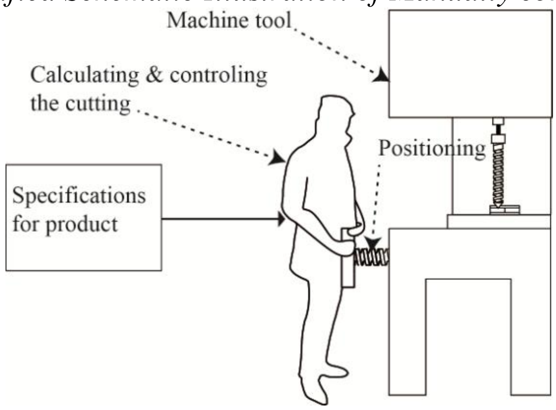
Traditionally, humans have used hand tools to process raw materials in order to create artefacts. The use of such tools can be physically demanding and time-consuming. To produce good quality items often requires a high degree of skill and knowledge of techniques such as joining, cutting, forming and finishing. Artefacts produced in this way are, however, unique as the craftsmanship varies from person to person.

Replacing hand tools with mechanized, machine tools reduces the physical requirements of the work for the operator; it also reduces repetitive actions (Schindler, 2007). A machine tool is defined as a device that uses energy to substitute repetitive physical human operations (Schindler, 2007). Using a manually controlled machine tool requires a skilful operator who, by processing information, manually operates the machine. Thus, the machine must be correctly set up following the manufacturing specifications of the product being made, and the operator must be able to interpret the engineering drawing of the product (Levary, 1995).

Evolution of the Machine through Numerical Control Technology

There is a great deal of manual intervention required to use a manually controlled machine. The operator is required to intervene at almost every stage of the process (Figure 1). *Numerical Control (NC)* technology was developed in the 1950s to attempt to eliminate the effect of variations in the skill of different operators using and setting the machine to manufacture a specific product, as well as to increase manufacturing accuracy and minimize production time (Levary, 1995). This technology '*controls the operation of machines automatically by means of symbols or numbers rather than by the manual turning of wheels and pulling of knobs*' (Levary, 1995). A simplified diagram of an *NC* mechanism as used in a machine tool is shown in Figure 2.

Figure 1. *A Simplified Schematic Illustration of Manually controlled Machine*



To create a *Part Program*, an operator converts the design specification into numbers and symbols. These numbers and symbols are converted to electrical signals in the *Machine Control unit*. The *Part Program* is fed into the machine via an external medium such as a punched paper or magnetic tape. Therefore, it is the program on the tape that controls the position of the *work piece* relative to the *cutting tool* during the manufacturing process (Pabla & Adithan, 1994). When manufacturing products using an *NC machine,* the operator has to select the type of *cutting tools* to be used, as well as control the "speeds and feeds". Therefore, whilst creation of complex forms by *NC* machine is not easy, it has enabled easier and more accurate mass production of objects (Pabla & Adithan, 1994).

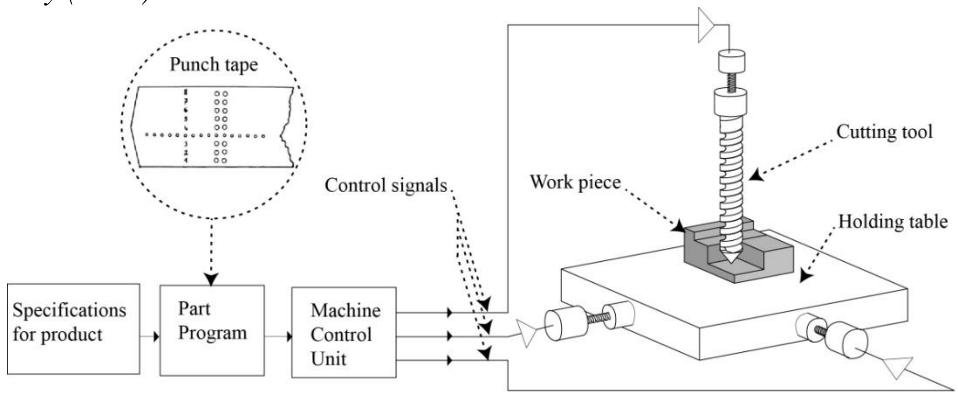
Evolution of the NC Technology through Computers – The Information Age

Using an *NC* machine, the *Part Program* has to be run each time a part is produced. In addition, minor changes in the design of the part mean that the existing tape containing the *Part Program* has to be discarded and a new one created. In the 1970s, computers were used for the first time with *NC* systems, so not only were issues with tapes solved but also there was a greater flexibility in production. With a *Computer Numerical Control (CNC)* machine, a complete *Part Program* is input and stored in the computer's memory (Pabla & Adithan, 1994). The computer sends the commands for each operation to the

Machine Control Unit, meaning that a computer controls the movement of the cutting tool and the work pieces. Thus, *CNC* technology is as cost effective at producing one-off pieces as it is at producing large numbers of the same piece.

CNC technology has enhanced most of the manufacturing processes being used currently. Such developments transform information, in this case transforming design information into the *Part Program* required to drive a *CNC* machine, and thus changing the human interaction with the process from physical to mental.

Figure 2. *A simplified Schematic Illustration of an NC Machine adapted from Levary (1995)*



Computers in Architecture

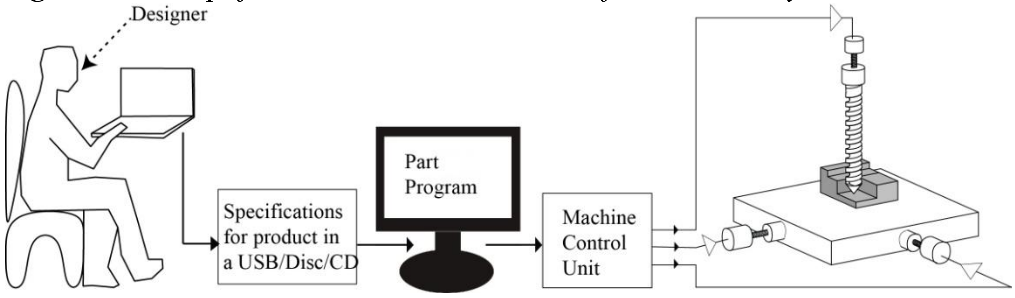
The origins of the use of computers in design are not as clear as they are in manufacturing. The first use of computers in architectural world was with the arrival of *Computer Aided Design Drafting (CADD)* (Seletsky, 2005). It has been seen as a progressive step up from manual drafting, but was mainly a replacement of '*one representational methodology for another*' (Seletsky, 2005). There is a more significant transformation in the architectural design world now taking place as electronic drafting evolves into *Computer Aided Design (CAD*) software. This was initially developed in the 1960s by the aircraft and automotive industries for use in the area of 3D surface construction and *NC* programming.

CAD does more than just drafting: it aids the whole design process by using computers as modelling tools which are capable of storing accurate 3D-volumetric descriptions of designs along with their non-graphical attributes, as well as allowing for analysis, simulation, and fabrication processes coupled with graphical representation (Bedworth, Henderson, & Wolfe, 1991). Using CAD, a designer can interactively improve their design, based on the results of analyses performed by the computer. Therefore, in the design world, it is not considered to be a representation tool but a performative one.

Interaction between Software and Hardware

The introduction of computers into both the design and the production processes has helped to improve productivity. Such a system is referred to as a *computer aided design and computer aided manufacturing (CAD/CAM)* system (Harp, 1985). In *CAD/CAM,* the software converts the design produced by *CAD* software into instructions that control machinery, such as a cutting tool (Figure 3). *CAD/CAM* systems have been adapted by other manufacturing industries such as the car industry and shipbuilding for use in the production of complex products (Corser, 2010). The advances in these technologies and the advantages they convey to their operator have taken the subjects of architectural debates in new directions. These technologies enable curvilinear and more complex geometric forms to be designed, manufactured and assembled more easily and more cost-effectively than using traditional construction technologies (Kolarevic, 2003c)

Figure 3. *A Simplified Schematic Illustration of CAD/CAM System*



Digital Architecture and the Conception

The use of *CAD* technology in architecture world has led to emergence of varies trajectories and the new field of so-called digital architecture. According to Hatzellis (2006), '*Digital Architecture has emerged from technological appropriation*'. In this field, computer modelling, software and simulations combined with the imagination of the user are used to design and construct a building. *CAD* technology performs complex calculations that architects otherwise find difficult to do, and allows a diverse range of complex forms to be created easily (Hatzellis, 2006). Runberger (2011) notes three emerging trajectories with in this field: 1) Integration of *CAD* into construction workflow in order to describe building parts in a more intelligent way and increase production consideration in the design process, 2) interest in exploring the potential of new technology for architectural form which has a common ground with contemporary expression in architecture partly based on technologies for design support and fabrication, 3) interest in computational processes and the way they can change our way to analyze generate and produce architecture. The first trajectory has originally emerged out of employment of *CAD* by product developers, managers and constructors. This trajectory leads to the topic often referred to as Building Information Modelling (*BIM*), which is well beyond the scope of this paper. The second and third are ongoing trajectories that have been emerged from employment of *CAD* by architects and designers. In many cases they are found together seamlessly or associated to each other. The former is however the key to this paper; in particular in regards to the emergent technologies for design support and fabrication.

Within these trajectories certain design techniques are employed. Leach (2011) believes that contemporary use of *CAD* by architects have led to emergence of two distinct techniques of parametric and algorithmic in design. Employment of these techniques in design stage has opened a new field of possibilities for architectural practice.

Parametric Technique

Monedero (2000) defines parametric design as the creation of an object using a set of parameters that defines the geometric relationships between elements of the design. It is a method of linking dimensions and variables to geometry in such a way that when the values change, the shape changes as well. Parametric design enables a flexible, modifiable, deformable and reactive type of modelling. In such associative geometric modelling, a collection of mutually connected elements has the ability to update itself according to modifications made to neighbouring elements (Ucar, 2006).

In digital architecture definition of parametric is not only bounded with consistent relationship between objects but also with such relationship between the objects and the external parameters such (prevailing wind, direct sun light, snow draft, etc). Therefore a design that associates the variation of external features and dynamic forces of the relative site, to the associative geometry of the intended building, is also defined as a parametric design. Using a parametric modelling system, the information related to these features and forces are stored in variables assigned to a parameter that direct the formation of the object. By doing so, either different configurations of the same object, or completely different objects, are created (Kolarevic, 2003b). Parametric design has a strong grounding in contemporary architecture. This design technique enables the architect to examine a range of designs that take into account various variables like environmental one, simply by altering parameters. This makes digital architecture, which uses computers as its main tool, an ideal test bed. In this system, the parameters are defined but not the shapes.

The best example of such geometric association is the massive curved roof of the *International Terminal* at *Waterloo Station* in London, designed by the firm of architects, Nicholas Grimshaw and Partners. The curve, which gradually expands towards the station end, consists of 36 dimensionally different but identically modelled arches (Szalapaj, 2001). Because of the asymmetrical geometry of the platform, the structure of the roof gradually rises on one side and gradually declines on the other side along the building. The main parametric relationships here described the structural form of the roof, in which the span and curvatures of individual arches were related. These relationships in turn determined the dimensions and topology of the trusses. The construction of the complex and variable size and shape of each arch was possible because of the application of structural analysis *CAD* techniques and the ability to calculate parametric relationships.

Algorithmic Technique

Algorithm is a specific method to create a mathematical process in solving problems. An algorithm is simple instruction for calculating a function. It can be a hand written process, e.g. set of equations, or a digital process or processor. According to Leach (2011), in the field of digital architecture, algorithmic technique refers to:

> '*The use of scripting language that allows the designer to step beyond the limitation of the user interface, and to design through the direct manipulation not of form but of code*.'

An important aspect of algorithm design is creating an algorithm that has an efficient run time. It is important to understand that '*algorithmic techniques are based on the use of code while parametric techniques are based on the manipulation of form*' (Leach, 2011). In many cases the parametric technique is embedded within algorithmic technique.

Using these tools and methods, digital architect is able to take account of environmental influences rather than simply defining a final shape. Kolarevic (2003b) notes that '*for the first time in history, architects are designing not the specific shape of the building but a set of principle…*'. Digital architecture is directed towards a form-finding technique. *CAD* has enabled a test ground for architectural design stage through integration of the information. However, Sevaldson (1999) noted that:

> '*Mostly the computers serve as an aid to speed up and rationalise the workflow, reduce errors or to monitor logistics, while the way designers work in principal stays unchanged. Still we like to think of the computer as a qualitative aid to the design process*.'

Architectural form has to engage and respond to dynamic influences from environmental and socio-economic forces (Kolarevic, 2003b). The architect Greg Lynn has contributed crucial new ideas and techniques to the adaptation of design methods to the new technology. To him, the abstract space of design is conceived as "an environment of force and motion rather than as a neutral vacuum" (Lynn, 1999).

Finally using the parametric and algorithmic techniques enables a higher degree and relatively more precise influence of quantitative and measurable parameters in the formation of conception and eventually architectural form. Design is a complex process that involves the consideration of both quantitative parameters (geometrical properties of the site, orientation, views, prevailing winds, noise pollution factors, construction restrictions, building programmed requirements, budgetary restrictions, fabrication requirements, material properties, etc) and qualitative parameters (cultural context, political will, social needs, aesthetic prototypical references, etc). The non-measurable/qualitative factors are as important as the measurable one in the conceptualization and generation of architectural form. Therefore it is important to emphasize that using digital tools does not and must not put aside the qualitative aspect of architecture. These aspects are involved in the design process through architect's cognition as they have been previously.

Rebirth the Complexity in Digital Architecture

When the abstract space of design is conceived as an environment of force, it embraces information and eventually becomes more complicated, interwoven and complex. Digital tools allow the integration of large amount of information with the design, enabling the production of complex forms. Some view such complexity as a problem, however Hatzellis (2006) argued that complexity is a part of digital design and gives it meaning. He further noted that the theory of complexity goes beyond it being just the opposite of simplicity and drawing on previous work that examined the link between beauty, complexity and performativity noted that:

> '*Prior to the digital age, simplicity was desirable as it was easier to calculate without errors. This is no longer the case as computers allow, within a certain range, extreme complexity in the areas of formulation, calculation and construction.*'

An example of complexity in terms of the conceptualization of a building is an Eskimo igloo. Eskimos, out of sheer necessity, have had to optimize the shape of an igloo so that it performs in the environment in which it is used. The igloo is complex in its form and construction. Relationships between architectural forms and their environment such as is seen with the igloo, have been lost in the course of industrialization and modern design (Fitch & Bobenhausen, 1999). This is due to particular circumstances of the 20th century being: 1- needs, for the low cost lodging that could be constructed speedily, and the high standard and modern life in the wake of the war, 2- abilities, for assembling and machining that led to certain production methods, 3- new materials that enabled long span construction and invention of new technologies (pluming, *HVAC* being heating, ventilation, and air-condition). In the circumstances of the 20th century, reduction of complexity was desired. Likewise today's circumstances such as need for energy saving, ability to integrate varies information into design and direct link of *CAD/CAM* via digital technologies, new material, and etc, enable reintroduction of complexity into architecture.

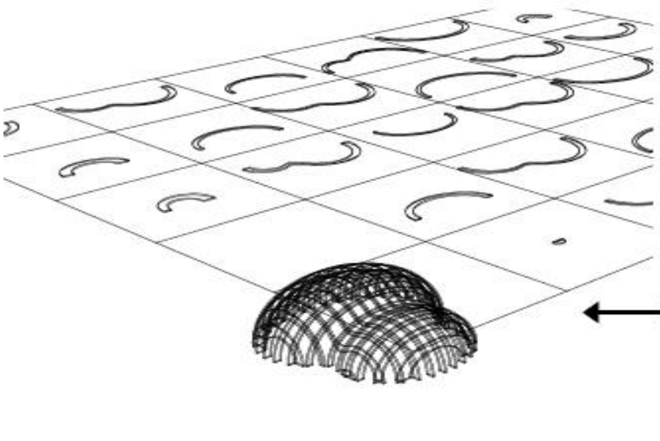
Within digital architecture, complexity appears at different stages, to different degrees and in different kind. In relation to digital design and construction complexity appears in: 1- the process, when handling the increased amount of information and as knowledge is integrated between the environmental designs, structural design, and architectural design, materialization, and fabrication and construction stages, and 2- in the physical body of architecture, being creation of complex and curvilinear surfaces by architects.

The complexity of the information and the power of *CAD* technology maybe one of the reasons that architects create complex and curvilinear surfaces but not the ultimate one. Except architecture forms, many contemporary products that surround us, from a toothbrush to a mobile phone to a car characteristically have smooth, rounded corners (Kolarevic, 2003b). In addition Complex forms in architecture are not any new ideas. Before the *CAD* and *CAM* technology, the design and realization of complex forms were by finding methods for physical form. Pioneer architects have manage to design and realize their complex and free forms, like Gaudí by hanging chain models (Collins, 1960) and Frei Otto (Nerdinger, 2005) by observing soap bubbles. Many Engineers such as Felix Candela and Heinz Isler (Chilton, 2000; Nordenson & Candela, 2008) were able to realize their curvilinear forms by implying geometrical knowledge over modern material, in this case concrete. Due to the communication gap between design tools and production tools, the production of these complex forms were singularly and costly.

Transactions from the Digital World to the Physical World

The digital information embedded in *CAD* models can be translated into control data that can directly drive the *CNC* machinery used for the fabrication and construction of a product (Figure 4). Kolarevic (2003c) presented the following four fabrication techniques that use this type of technology to realize digitally-generated, complex, geometrical objects.

Figure 4. *Complex Forms are Built up of Non-standard Geometries. The Non-Standard Geometries are embedded with Digital Data shown in the Right Side. These Data are the Specification of Products (Figure 3) that Feeds the* ***Part Program*** *of a CNC Machine*



[Data]

Z	Y	X
-0.640355	-4.99559	0.1323
-0.640412	-4.99555	0.1335
-0.639644	-4.99552	0.1344
-0.639336	-4.99539	0.1383
-0.639295	-4.99534	0.1398
-0.639268	-4.99535	0.1395
-0.638735	-4.99531	0.1407
-0.638151	-4.99532	0.1404
-0.636204	-4.99519	0.1443
-0.635432	-4.99493	0.1521
-0.635056	-4.9948	0.156
-0.634572	-4.99478	0.1566
-0.633757	-4.995	0.15
-0.632524	-4.99489	0.1533
-0.631771	-4.99475	0.1575
-0.630903	-4.99497	0.1509
-0.630823	-4.99499	0.1503

Cutting Techniques

Cutting techniques are used in two-dimensional fabrication and involve the movement of the cutting tool in two axes in relation to the work piece, which can be a sheet of material for example. Different technologies exist for different cutting techniques; techniques vary with the material to be cut.

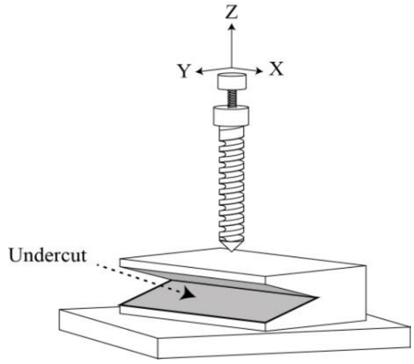
Technologies, such as laser cutting and electronic discharge machining, are based on the use of thermal energy to cut and so melt or burn the material in order to cut it. Technologies for smoother cutting, such as water jet cutting, punching and blanking, die cutting, and glass scoring are mechanically based techniques and it is erosion, therefore, that cuts the material. Rarely used in architecture, photochemical machining is a chemically based cutting technique.

Subtractive Techniques

Subtractive techniques are used in three-dimensional fabrication. They involve the reduction and removal of material from a solid block. These techniques use a variety of chemical, thermal and mechanical technologies.

The most common technology used in the architectural world is the *CNC* milling router, which is a mechanically based technology. It uses a combination of drilling, turning and grinding to remove material. The milling machine is axially constrained. Milling of a solid in three-axes is an extension of two-dimensional cutting but with the ability to move in the Z direction. The range of shapes that can be produced by this type of machine is limited, as it cannot produce the undercuts shown in (Figure 5). For those shapes requiring undercutting, a four- or five-axis milling machine is used.

Figure 5. *Undercuts (Kolarevic, 2003c)*



The *CNC* milling machine has been widely used in the architectural world. The best example is the Walt Disney Concert Hall in Los Angeles. It consists of stone panels that are geometrically double curved. These panels were *CNC* milled in Italy, then shipped to Los Angeles to be assembled on a steel frame at the site.

Formative Techniques

Formative fabrication shapes material by deformation or reshaping using mechanical forces, applying heat or steam, and moulding the material in order to achieve the desired form. There are many *CNC* machines that can be used for formative fabrication. Dependent on the material that is being shaped, there are machines that assist steam bending, simple wood lamination, composite wood lamination and the shaping of molten glass and plastics. A comprehensive study of the technologies used in formative techniques has been presented by Thompson (2007).

Additive Techniques

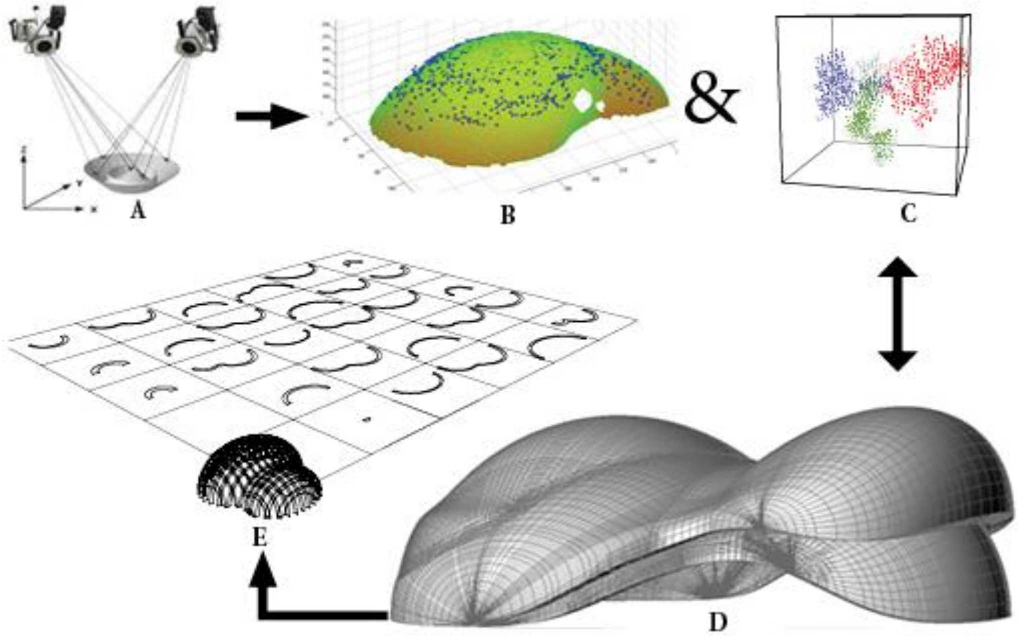
Additive fabrication is the formation of an object by adding material, layer by layer. It is referred to as solid freeform fabrication, layer-by-layer manufacturing, and rapid prototyping. The methods used for this technique are based on light, heat or chemical reactions. There are many different technologies that exist such as Stereolithography (*SLA*), Selective Laser Sintering (*SLS*), 3D Printing (*3DP*), Fused Deposition Modelling (*FDM*) and Multi-Jet Manufacture (*MJM*). However, due to the expensive equipment, time-consuming production and limitations in the sizes of the object that can be produced, this technique has limited applications in the field of building design and manufacture. There is a relatively new additive technology called "Contour Crafting" that has been invented and patented by Behrokh Khoshnevis of the University of Southern California, which allows rapid layer-by-layer pouring of concrete for use in full-scale building projects.

Transactions from the Physical World to the Digital World

The four techniques presented by Kolarevic (2003c) enable the translation of a digital object into a physical one. By using three-dimensional scanning techniques, it is possible to construct, or "reverse engineer", a digital model from its physical counterpart (Figure 6(A)). A few architects, such as Frank Gehry, use this technique to translate the physical geometry of a building to a digital representation. By doing so, different transformations can be applied to the digital representation that would not be possible with the actual building.

By scanning a physical object, point clouds can be created in the digital environment, which can be converted to an approximation of the real geometry. This technique enables the collection of data from the specific construction site and supports the conceptual framework with real-world data (Figure 6(A)(B)(C)). There are various types of three-dimensional laser scanners, with their use depending on the type of object being scanned.

Figure 6. *Collecting Geometric Data of Site through 3D Scanner (A). Creation of the Site Geometry as Point Clouds in Digital World (B). Resembling collected Data such as Orientation, Views, prevailing Winds, Noise Pollution, Daylight and etc in Digital World to support the Conceptual Framework with Real-world Data (C). Generation of form based on the Precedent Inputs from Architect's Cognition and the collected Data (D). In Addition, Step (D) Presents the Possibility for Geometrical Adjustment in the Design Process in Favours of previously defined Parameters for Geometry of Form. Rationalizing the Form for Prefabrication (E)*



Digital Fabrication and Complexity

In the Information Age, the ability to link the digital and physical worlds has radically reconfigured the relationship between conception and manufacture.

In the architectural world, the introduction of consumer *CNC* routers and laser cutters, together with 3D printers has enabled rapid prototyping of the complex geometries encountered in architectural design (Scheurer, 2008).

Complex forms are built up of non-standard geometries and contain a large number of non-standard parts (Figure 6 (E)). These parts are embedded with digital data that can be read by CNC machines (Figure 4). Scheurer (2008) noted that development of *CNC* machines has made it possible to fabricate individual parts at nearly the same cost as if they were mass produced (Figure 4). However, he argued that when scaling up these complex forms to life-size, their production using existing *CAM* systems is not appropriate. According to Scheurer (2008) , it is sometimes more efficient to use a custom-built *CAM* system and tailor-made fabrication for this kind of geometry.

Scheurer (2010) believes that current technology has shifted the complexity of the process away from the machining of material and towards the processing of information. Although parametric and algorithmic design makes it easier for an architect to handle complexity, it does not reduce the degree of complexity from the project. Scheurer (2010) argued that within parametric and algorithmic design modelling the same degree of complexity is defined but in a different language. Instead of struggling with a set of drawings, the designers are forced to create a clever algorithm, which requires a high degree of thought.

Discussion and Conclusion

The development of machine tools led to the creation of mass-produced objects that are exact copies of each other, because subsequent changes in design required human intervention and were time-consuming. Machine tools evolved into computer-controlled devices, thus eliminating manual intervention during the production process. As a result, parts with different shapes could be produced almost as cost-effectively as standard ones. In addition, the use of computers during the design stage enabled information, in the form of digital data, to be transferred between design tools and manufacturing machines.

Use of *CAD* technology in architecture has pushed the boundary of conceptualization towards the use of real-world data, and this has led to unexpected complexity. The parametric-algorithmic design method has enabled a diverse range of concepts to be tested and has led to derivation of plausible forms (Figure 6(d)).

Ability of *CAD* to integrate large amounts of data into a design has led to the use of complex geometric parts in buildings. The production of these parts is now as rapid and cost-effective as that of standardized parts as a result of the use of *CNC* fabrication technology.

Data embedded in geometries from *CAD* systems can now be used to control directly *CNC* machines (Figure 4). Other data about condition of site can be inputted and varied by the designer to test how geometry of parts that they have designed is affected (Figure 6(d)). Therefore, Limitations in the manufacturing of a product have moved from the hardware to the software that creates the machine data and handles the data transfer. Tailor-made or custom fabrication has become more cost-efficient in the production of buildings that have complex geometric forms.

It is now no longer necessary to limit a design to simple shapes. The technological advances in *CAD* and *CAM* systems have allowed products to be varied, be highly specialized and have high performativity whilst also being able to be manufactured cost-effectively. The new digital architects have found this new technology profoundly important for the creation and realization of high quality buildings. The quantity of information that has to be handled and processed has increased as these tools have evolved. Therefore, in order to be able to produce complex geometric parts as effectively and as economically as simple, symmetrical parts, it is suggested that more study on the handling and processing of such information is undertaken. It is also necessary to underline and highlight the degrees and kinds of complexities within the process.

Acknowledgment

This paper is a part of the ongoing project called Nya Giron, which means New Kiruna in English. This is a project that is being undertaken to transform and relocate the city of Kiruna, Sweden. The major part of this city must be relocated and rebuilt due to the ground deformation caused by the mining industry. The author of this paper hopes it will give a better understanding of the conceptualization and methods of production of these new buildings. I would like to thank my Architect friend, Reza Askari for his constant reviews, critics and suggestions on this paper.

References

Armstrong, P. (2009). *From Bauhaus to m-[h] ouse: The Concept of the Ready-Made and the Kit-Built House*.

Bedworth, D. D., Henderson, M. R., & Wolfe, P. M. (1991). *Computer-integrated design and manufacturing*: McGraw-Hill.

Chilton, J. (2000). *Heinz Isler*: Thomas Telford.

Collins, G. R. (1960). *Antonio Gaudì*: George Braziller.

Corser, R. (2010). Introduction: Readings: Looking Back at Recent Discourse in Emerging Technologies. In R. Corser (Ed.), *Fabricating Architecture: Selected Readings in Digital Design and Manufacturing* (pp. 9-19): Princeton Architectural Pr.

Davies, C. (2005). *The prefabricated home*: Reaktion Books.

Fitch, J., & Bobenhausen, W. (1999). *American building: the environmental forces that shape it*: Oxford University Press.

Giedion, S. (2007). Construction.Industry.Architecture. In W. W. Braham, J. A. Hale & J. S. Sadar (Eds.), *Rethinking technology: a reader in architectural theory* (pp. 37-41): Taylor & Francis.

Harp, J. (1985). CAD/CAM: BACK TO BASICS. *Manufacturing Engineering, 95*(4), 61-63.

Hatzellis, S. (2006). Formal complexity in Digital Architecture. In A. Ali & C. Brebbia (Eds.), *Digital architecture and construction* (pp. 51-58): Wit Pr/ Computational Mechanics.

Jeanneret-Gris, C. E. (2007). Engineer's Aesthetic and Architecture. In W. W. Braham, J. A. Hale & J. S. Sadar (Eds.), *Rethinking technology: a reader in architectural theory* (pp. 32-36): Taylor & Francis.

Kieran, S., & Timberlake, J. (2004). *Refabricating architecture: How manufacturing methodologies are poised to transform building construction*: McGraw-Hill Professional.

Kolarevic, B. (2003a). *Architecture in the digital age: design and manufacturing*: Taylor & Francis.

Kolarevic, B. (2003b). Digital morphogenesis. *Architecture in the Digital Age: Designing and Manufacturing, Taylor and Francis, Oxon, UK*, 11-28.
Kolarevic, B. (2003c). Digital Production. In B. Kolarevic (Ed.), *Architecture in the digital age: design and manufacturing* (pp. 1-10): Taylor & Francis.
Leach, N. (2011). Discussion on Parametric and Algorithmic technichs [draft: Parametric Explained], (Personal communication, 23 October 2011).
Levary, R. (1995). Fundamentals of computer numerical control. *International journal of computer applications in technology, 8*(3-4), 211-222.
Lynn, G. (1999). *Animate form*: Princeton Architectural Pr.
Monedero, J. (2000). Parametric design: a review and some experiences. *Automation in construction, 9*(4), 369-377.
Nerdinger, W. (2005). *Frei Otto : complete works : lightweight construction, natural design*. Basel ; Boston: Birkhäuser.
Nordenson, G., & Candela, F. (2008). *Seven structural engineers: the Felix Candela lectures*: The Museum of Modern Art.
Pabla, B., & Adithan, M. (1994). *CNC Machines*: New Age International.
Runberger, J. (2011). *Architectural Prototypes, Doctoral thesis* , [Draft] KTH school of Architectural and Built Environment.
Scheurer, F. (2008). Architectural CAD/CAM: Pushing the Boundaries of CNC Fabrication in Building. In B. Kolarevic & K. R. Klinger (Eds.), *Manufacturing material effects: rethinking design and making architecture* (pp. 211-222): Routledge.
Scheurer, F. (2010). Materialising Complexity. *Architectural Design, 80*(4), 86-93.
Schindler, C. (2007). *Information-Tool-Technology: Contemporary digital fabrication as part of a continuous development of process technology as illustrated with the example of timber construction*.
Seletsky, P. (2005). Digital Design and the Age of Building Simulation, IN. *ACEbytes Viewpoint, 19*.
Sevaldson, B. (1999). Research on digital design strategies. *Institute of Industrial Design*.
Spuybroe, L. (2009). The Architecture of Variation Thames & Hudson
Szalapaj, P. (2001). Parametric Propagation of Form. *Architecture Week, 19*.
Thompson, R. (2007). Forming Technology. In *Manufacturing processes for design professionals* (pp. 22-232): Thames & Hudson.
Ucar, B. (2006). *An Assessment Of The Architectural Representation Process Within The Computational Design Environment*. Middle East Technical University.
Woudhuysen, J., & Abley, I. (2004). *Why is construction so backward?*: Wiley Academy.
Wouldhuysen, J., Kieran, S., & Timberlake, J. (2010). Mass Customization and the Manufacture Module. In R. Corser (Ed.), *Fabricating Architecture: Selected Readings in Digital Design and Manufacturing* (pp. 128-137): Princeton Architectural Pr.