ADVANCED DIGITAL MANUFACTURING TECHNIQUES (CAM) IN ARCHITECTURE AUTHORS

HAZEM M. N. AFIFY AND ZEINAB A. ABD ELGHAFFAR
Menoufia University, Egypt
Hazemmafify@yahoo.com
Ain Shams University, Egypt

Abstract: Building projects today are not only born out digitally, but they are also realized digitally through "file-to-factory" processes of computer aided manufacturing (CAM) and computer numerically controlled (CNC) technologies. It was the challenge of constructability that brought into question, what new instruments of practice are needed to take advantage of the opportunities opened up by the digital modes of production, instead of whether a particular form is buildable. In this case of building construction, architects could design with attention to innovative details, afforded by unique shapes and sizes, knowing that whatever they created on their computer screen could be fabricated digitally for an affordable price. The aims of the research are to discuss and analyze the digital manufacturing techniques (CAM) in architecture and its fabrication, production process. To understand how these technologies fit within a broader context of architectural practice. The research begins with defining, what is digital manufacturing in architecture, its potentials, components and influences in the contemporary architecture. Further more it discusses the digital fabrication, Two- dimensional cutting, subtractive fabrication, additive fabrication and formative fabrication. The assembly technique, building skin, new materials and mass-customization in digital manufacturing techniques (CAM). That will be a hand in analyzing several case studies.

Keyword: Digital technology in architecture, Digital manufacturing, Formative fabrication, New materials, Fabrication machines and software.

1. A New Design and Manufacturing Paradigm

The advances in computer aided design (CAD) and computer-aided manufacturing (CAM) technologies in the last few years especially since the mid-1990s, started to have an impact on building design and construction practices. The generative and creative potentials of digital continuum and tools, together with manufacturing advances began as a response to industrialization in automotive, aerospace and shipbuilding industries and called for architects to master the means of production in an attempt to remain engaged in the qualitative aspects of crafting buildings (Rotheroe, Kevin Chaite, Manufacturing freeform architecture). New dimensions are opening up in architectural design and new means of manufacturing, by allowing production and construction of very complex forms that were, very difficult and expensive to design, produce and assemble using traditional construction technologies. A new digital continuum is established, a direct link from design through to construction and manufacturing. An integrated role happened between designers' thoughts, technical consultants, provided by the online database and software agents, all are inputs to produce a digital model / physical model. The outputs of these models are the drawings, images, animations, VIR, analytical reports…….and fabricated construction components done by CAD/CAM facilities (Mitchell, McCullough, Digital Design Media, 1995) Fig.1.

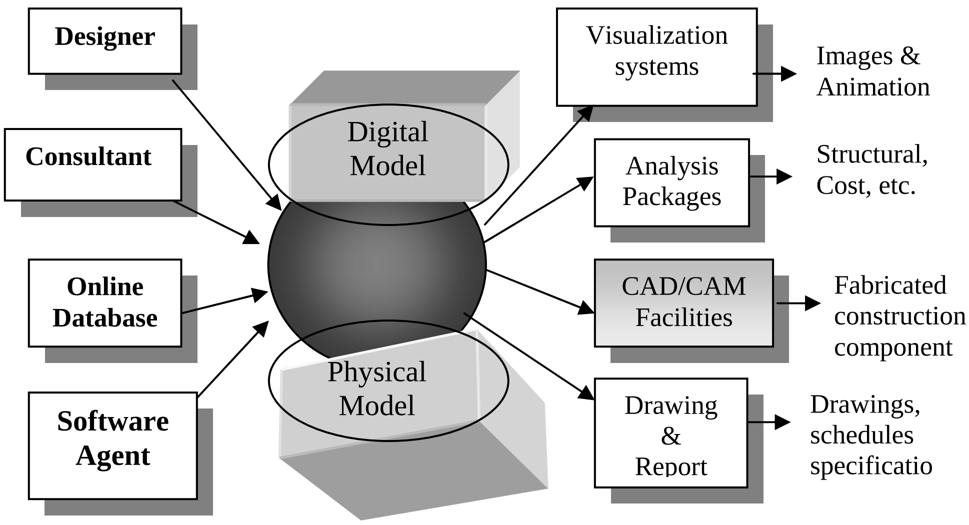

Figure 1 The integrated roles towards a digital Model,
Source: Mitchell, McCullough, Digital Design Media, 1995

2. Three- Dimensional Design Process

Building projects today are not only born out digitally Fig.2. In the beginning, and most important, is the architect's thought and idea, which is translated through sketches. Then comes the role of appropriate software which transfers all this into Three- dimensional digital Model. In the process of design development for some designers such as Frank Gehry, the 3D digital model remained a 2D "Flat" digital manipulation of surfaces on a computer screen (Ragheb, J.Fiona, Frank Gehry, Architect – 2001- pp.360).

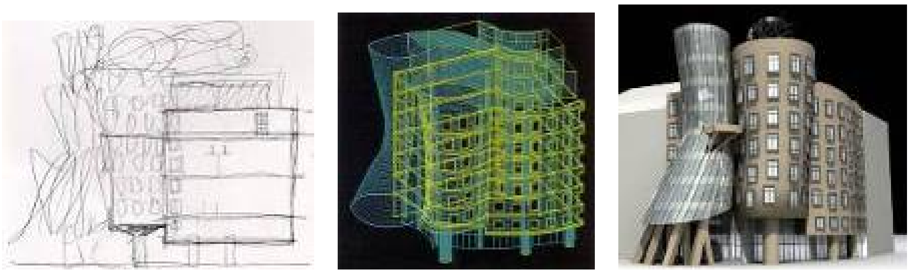

Figure2 The idea of building as sketch, then, digital Model, after that a phisical model by 3D printer. The Nationale-Nederlanden Building – Prague- Architect F.Gehry, 1995
Source: Ragheb, J.Fiona – Frank Gehry, Architect – 2001

It is needed to fabricate 3D study model with complex curvilinear geometries in a material form, the digital model, by using the 3D printer Fig.3. This process is considered the beginning of the digital fabrication on the design level. The information data of the digital model is translated by CAM computer- aided manufacturing software that generates the CNC computer numerically controlled instructions which are transmitted to the fabrication equipment like 3D printer (milling machine)[1] .

The architect makes some development on the study model and through 3D scanner he can produce again "build back" a digital model in a process often referred to as "reverse engineering." A pattern of points, called the "point cloud" is created from the physical model through scanning, and is then interpreted by the conversion software to produce a close

[1] The CNC software makes a sequence of instructions for the fabrication machine, first slice up the digital model into thin, horizontal layers. Then, for each of these layers, it must develop a scanning sequence for deposition of tiny pellets of plastic to create the layer. Eventually, the complete design is fabricated in layer-by-Layer fashion.

Figure 3 CNC software 3D printer *Figure 4* Model being digitized by 3D scanner, EMPproject, 1995-2000

Source: Denford Company, Product Catalogue- 2007
Ragheb, J.Fiona – Frank Gehry, Architect – 2001

approximation of the model's geometry (Goldberg, Edward H. "Scan Your World with 3D Lasers", 2001. Fig.4. This final 3D CAD "mother" model has the principal element, component sizes and all relevant data of all different parts of the building, from this model the different building team members will start their own co-engineering Fig.1.

3. Digital Fabrication, File to Factory

Digital fabrication starts the work from the 3D-CAD mother model. The first step is analyzing the information data structurally for all parts of the building through CAM software, the second step is translating all the analyzed information to CNC computer numerical controlled, which produce it in the form of certain instruction to the different appropriate fabrication machines in the factory for every part of the building "File to Factory". This processes is based on; two- dimensional cutting, subtractive, additive and formative fabrication (Schodek, Daniel, Digital Design and Manufacturing, 2004).

3-1. Two- Dimensional Cutting

It is the most commonly used fabrication technique. Various cutting technologies, such as plasma-arc, laser-beam and water-jet, involve two-axis motion of the sheet material relative to the cutting head, and are implemented as a moving cutting head, a moving bed or a combination of the two. The differences between these technologies are in the kinds of materials or maximum thicknesses that could be cut.

For example in the Dynaform pavilion, the supporting structure is based on an orthogonal set of sequential 16 different frames (sections) made from the steel posts.

Figure 5 CNC plasma cutting of steel sheet, Welding, fabrication of the hollow box steel girders, Assembly of the steel structure of Dynaform, 2002, Frankfurt am Main, Germany
Source: http--www_gregull-spang_de-_content-Referenzen-Bilder-Messehallen-BMW.htm

More than 30,000 individual pieces were cut using computer-driven plasma-cutters. The curved cutting paths had to be calculated using a special program CNC and welded by hand to very tight tolerances to form the hollow box steel girders (Kolarevic, Branko, Architecture in the digital age, 2005, p.34, 137.) fig 5.

3-2 Subtractive Fabrication

It involves the removal of a specified volume of material from solids using electro-, chemically- or mechanically-reductive (multi-axis milling) processes. The milling can be axially, surface or volume constrained. In axially constrained devices, such as lathes, the piece of material that is milled has one axis of rotational motion. The milling of three-dimensional solids have the ability to raise or lower the drill-bit, to move it along *X*, *Y* and *Z* axis, the three-axial milling machines could remove material volumetrically. There are also four- and five-axis machines for special shapes. The CNC programs instructions control the motion, the feedrate, operation of the spindle drive, coolant supply, tool changes, and other operational parameters. As milling of shapes can be accomplished in a variety of ways and generating an appropriate "tool path", which is a sequence of coded instructions for the machine to execute.

For example The CNC multi-axis milling has applied to produce the formwork (molds) for the off-site and on-site casting of concrete elements with double-curved geometry, as was done in (Zollhof Towers, Germany, 2000- F. Gehry) (Rempen ,Thomas, der Neue Zollhof Düsseldorf , Germany, 1999). The undulating forms of the load-bearing external wall panels made of reinforced concrete, were produced using blocks of lightweight polystyrene (Styrofoam), which were shaped in CATIA program and were CNC milled to produce 355 different curved molds that became the forms for the casting of the concrete fig 6.

Figure 6 The CNC multi-axis milled Styrofoam molds, which are fitted and in site assembled
Source: Rempen ,Thomas, der Neue Zollhof Düsseldorf , Germany, 1999

3-3 Additive Fabrication

Additive fabrication involves incremental forming by adding materials in a Layer-by-Layer fashion, in a process which is the converse of milling. It is often referred to as layered manufacturing. The principle behind all additive fabrication technologies is that the digital model is sliced into two-dimensional layers (cross-section). The information of each layer is then transferred to the processing head of the manufacturing machine (Kolarevic, Branko, Architecture in the digital age, 2005 – pp.36, 37). This process is repeated until the entire model is completed. Because of the limited size of the objects that could be produced, they are used in construction to produce components in series, such as steel elements in light truss structures Fig 7, by creating patterns that are then used in investment casting.

Figure 7 Column components that have been CNC milled – after it fabricated
Source: http:/ www. architectureweek.com, Manufacturing Freeform Architecture

3-4 Formative Fabrication

In formative fabrication mechanical forces, restricting forms, heat or steam are applied to a material so as to form it into the desired shape through reshaping or deformation, which can be axially or surface constrained. For example, the reshaped material may be deformed permanently by such processes as stressing metal past the elastic limit, heating metal and then bending it while it is in a softened state, steam-bending boards, etc. Double-curved, compound surfaces can be approximated by arrays of height-adjustable, numerically-controlled pins, which could be used for the production of molded glass and plastic sheets and for curved stamped metal. such as Wave BMW pavilion (Kolarevic, Branko, Architecture in the digital age, 2005- pp.38- 134).

Figure 8 Tht extended aluminum profiles were bi-directionally bent with data-driven bending machines – The rods are different and all joints are identical ,BMW pavilion, designed by Bernhard Franken, 2000,
Source: Kolarevic, Branko, Architecture in the digital age, 2005

4. Assembly

After the components are digitally fabricated, their assembly on site can be augmented with digital technology. 3D CAD/CAM model can be used to precisely determine the location of each component, move each component to its location and fix it in its proper place. Such new digitally-driven technologies, like electronic surveying and laser positioning are increasingly being used on construction sites around the world to precisely determine the location of building components (Kolarevic, Branko, Architecture in the digital age, 2005- pp.38).

For example, Guggenheim Museum in Bilbao was built without any tape measures. During fabrication, each structural component was bar coded and marked with the nodes of intersection with adjacent layers of structure. On site bar codes were swiped to reveal the coordinates of each piece in the CATIA model. Laser surveying equipment linked to CATIA enabled each piece to be precisely placed in its position as defined by the 3D CAD/CAM model(LeCuyer, Annettle , "Building Bilbao" in Architectural Review, 1997, vol. 102, no. 1210, pp. 43-45.) Fig 9 .Similar processes were used on BMW pavilion, designed by Bernhard Franken Fig 10.

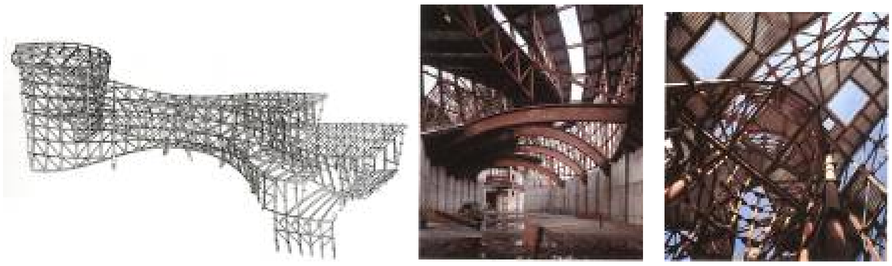

Figure 9 Guggenheim Museum in Bilbao, the 3D model and the assembly of its componets
Source: LeCuyer, Annettle , "Building Bilbao" in Architectural Review, 1997

Figure 10 BMW pavilion, designed by Bernhard Franken, 2000,
Source: Kolarevic, Branko, Architecture in the digital age, 2005

5. Building Skin

Digital architecture today create and producing building skins that result not only in new expressive and aesthetic qualities, but also in new geometric complexities. The building envelope is increasingly being explored for its potential to reunify the skin and the structure. It is the surface and not necessarily the structure that preoccupies the work of the contemporary architectural in its exploration of new formal expression.

The skin of a building becomes necessarily emphasized due to the logics of formal conception inherent in the CAD (NURBS-based) software. That, in turn, prompted a search for "new" materials and "new" surface treatments with CNC techniques.

For example, the building skin of Victorian College of the Arts, that appears as morphological surfaces, a series of intersecting cones, some of which have their apexes penetrated to form circular windows while others are marked with small reflective domes[2]. A combined process of digital production CAD/CAM and explosive forming has developed to fabricate a range of 3D cladding panels from silver titanium sheets 0.85mm that are considerably different in size, curvature and depth. This process knows as "vacuum-injection method"[3].


Figure 11 Victorian College of the Arts, Melbourne, 2003- Minifie Nixon Architects
Source: (Aa) architecture Australia magazine, SAYING AND DOING, March/Ariel 2004

More over, the structure becomes embedded or subsumed into the skin, in which the skin absorbs all or most of the stresses. The principal idea is to conflate the structure and the skin into one element, thus creating self-supporting forms that require no armature, such as curves and folds that would enable the continuous skin to act structurally, obviating an independent static system. The fusion of the structure and the skin in monocoque and semi-monocoque envelopes has a considerable impact on the design of structures and cladding in particular.

For example, Aluminum semi-monocoque structures Fig 12. The structural elements were digitally cut out of 10 mm thick aluminum; the skin was made from 4 mm thick sheets of aluminum that were bent into doubly-

[2] Aa, architecture Australia magazine, SAYING AND DOING, March/Ariel 2004

[3] (In a water tank the metal sheet to be formed is placed on top of the mould and sealed; a vacuum in the mould cavity is produced. So the pressure load of the detonating explosive located on top of the metal is evenly distributed and forces the sheet into the mould. The vacuum ensures complete alignment of material and mould surface in the forming process.)

curved shapes using traditional boat building methods. The implications of these new structural skins are significant[4].

Figure 12 the *Georges Restaurant* (2000), Paris, by Jakob and MacFarlanein architect. Source: Kolarevic, Branko, Architecture in the digital age, 2005

6. New Materials

New forms of architectural expression and advances in material science have led to a renewed interest among architects in materials, their properties and their capacity to produce desired aesthetic and spatial effects. New materials for building skins are lightweight (unprecedented thinness), have high strength, dynamically-changing properties, functionally-gradient composition, and an incredible repertoire of new surface effects. These materials can also be easily shaped into various forms, such as titanium, high-temperature foams, fiberglass (glass fiber reinforced polyester GRP), polymers, rubbers, plastics, ETFE-Folien, PVC membrane and composites, all of these offer several advantages over materials commonly used in current building practice.

For example, the physical characteristics of fiberglass make it particularly suitable for the fabrication of complex forms. It is cast in liquid state, so it can conform to a mold of any shape and produce a surface of exceptional smoothness - a liquid, fluid materiality that produces liquid, fluid spatiality.
as produced in a memorial building for Jitzak Rabin, Israel fig 13. The concept was free spanning shells, a lightweight construction that would be made as giant surfboards of foam with GRP skin (glass fiber reinforced polyester), creating 5 different GRP sandwich roof wings with 30m* 20m and 8m long cantilevering wing.. The composite shells are a world

[4] Kolarevic, Branko, Architecture in the digital age, 2005- pp.42- 186

innovation for the construction sector ‘an amazing solution’, of which especially ‘liquid design’ schemes in architecture can make further use of.

Figure 13 manufacturing the roof using GRP and foam blocks of polystyrene as a mould
Architect Moshe Safdie. 2003-2005
Source: http://www.octatube.nl/rabincenter/en/imagegaller.html

Another example, the choice of material for the "Dynaform" was a major challenge. The structural frame for the 130 m long building covered by a transparent ETFE-Folien, PVC membrane. This material seemed to be the best alternative to glass, Plexiglas, concrete or metal, since it is light, flexible (its "moving" shape) and fire-resistant and can be shaped at low temperatures. The materials also allow the building to be dismantled and re-erected for future automobile exhibitions.

Figure 14 Because of its "moving" shape, the facade is covered by a one-layered printed Hostaflon ETFE membrane. The smart membrane details, such as supports of the clamping plate's door edgings, ETFE-fixation systems made this building a great success for the client
Source: http--www_gregull-spang_de-_content-Referenzen-Bilder-Messehallen-BMW.htm

7. Mass- Customization

Industrial manufacturing is based on building production with the logics of standardization, prefabrication and on-site installation. The rationalities of manufacturing dictated geometric simplicity over complexity and the repetitive use of low-cost mass produced components. These rigidities of production are no longer necessary, as digitally-controlled machinery can fabricate unique, complex-shaped components at a cost that is no longer expensive. Variety, no longer compromises the efficiency and economy of production. The ability to mass-produce highly differentiated building components with the same facility as standardized parts, introduced the notion of "mass-customization" into building design and production (it is easy and cost effective for a CNC milling machine to produce 1,000 unique objects as to produce 1,000 identical ones).

In buildings, individual components could be mass-customized to allow for optimal variance in response to differing local conditions in buildings, such as uniquely shaped and sized structural components that address different structural loads in the most optimal way, variable window shapes and sizes that correspond to differences in orientation and available views.

8. Conclusion

The most significant findings of this paper can be listed as follows:

- The generative and creative potentials of digital media, together with manufacturing advances already attained in automotive, aerospace and shipbuilding industries, are opening up new dimensions in architectural design and construction.
- The fabrication machines are considered as a device that automatically translates a digital object in a design model into a material realization.
- Design development software translates the digital solid model into a very different representation before physical fabrication actually takes place. This software produces a very long sequence of instructions for depositing pellets of the material, then the fabrication machine executes these instructions, one by one.
- With CAD/CAM fabrication, the crucial efficiency considerations are, first, the number of operations that must be executed to physically produce a given design. Second, the speed with which each operation can be executed. As the time taken to execute an operation decreases, the number of operations executable in a given time increases.
- The skin of a building becomes necessarily emphasized due to the logics of formal conception inherent in the CAD (NURBS-based) software. That, in turn, prompted a search for "new" materials and "new" surface treatments with CNC techniques.

- New materials for architectural skins offer the unprecedented thinness, dynamically-changing properties, functionally-gradient composition, and desired aesthetic and spatial effects
- The industrial production no longer means the mass production of a standard product to fit all purposes. Digitally-controlled machinery can fabricate unique, complexly-shaped components at a cost that is no longer prohibitively expensive.
- CAD/CAM design and manufacturing processes depends on three steps: First, developing software that allows exploring the design idea, whether it is concessive to this specific idea or extends to other projects.
  Second, deriving a digital model through the application of this software to convert it into a series of instructions.
  Third, Improving CAM fabrication machine to deal with these instructions to produce results that could not be achieved anyway else.

9. References

MERCER, P.A. AND SMITH, G., 1993. *Private viewdata in the UK.* 2nd ed.

London: Longman.

BANTZ, C.R., 1995. Social dimensions of software development. *In:* J.A. ANDERSON, ed. *Annual review of software management and development.* Newbury Park, CA: Sage, 502-510.

JOSEPH B. PINE. 1993, Mass Customization: The New Frontier in Business, USA, Harvard Business School Press,

KHOSHNEVIS BEHROKH, 1998, "Innovative Rapid Prototyping" in Material Technology,

KOLAREVIC, BRANKO, 2005, *Architecture in the digital age*, UK, Taylor &Francis

LECUYER, ANNETTLE, 1997, *Building Bilbao* in Architectural Review, vol. 102, no. 1210

MITCHELL, MCCULLOUGH, 1995, *Digital Design Media*, 2nd edition. New York, Van Nostrand Reinhold

RAHIM AII, 2002, (edJ, AD Profile 155) Contemporary Techniques in Architecture. London: Wiley,

RAGHEB, J.FIONA, 2001, Frank Gehry, Architect

REMPEN ,THOMAS, 1999, *der Neue Zollhof* , Düsseldorf , Germany, Bottrop

ROTHEROE, KEVIN CHAITE, 1993, Manufacturing freeform architecture, Amsterdam, Elsevier

SCHODEK, DANIEL, 2004 , *Digital Design and Manufacturing-Applications in Architecture and Design* , John Wiley & Sons

AA, ARCHITECTURE AUSTRALIA MAGAZINE, *SAYING AND DOING*, March/Ariel 2004