THE WAY ARCHITECTURAL MODEL AS A NEW COLLABORATIVE DESIGN ENVIRONMENT TALKS WITH MACHINES

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ABSTRACT

THE WAY ARCHITECTURAL MODEL AS A NEW COLLABORATIVE
DESIGN ENVIRONMENT TALKS WITH MACHINES

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The scope of this study is to illustrate the relationship between computer-aided design (CAD) and computer-aided manufacturing (CAM) systems, and to show how architectural modeling should be positioned in the process of computer-aided design/computer-aided manufacturing (CAD/CAM) systems. The integration of computer aided technologies with architectural design is investigated in terms of design-production/fabrication interaction. The research has been based on a case study in which the CAD/CAM process from the initial design phase to the actual manufacturing of the design object has been explored. A design object is modeled using CAD and the model is manufactured using CAM in order to illustrate the process of CAD/CAM and its potentials related to architectural design and the construction/manufacturing/fabrication process of building. Thus, the study tries to demonstrate what digital tools can provide to the field of architecture, and lists the requirements for architectural modeling to acquire compatibility among the parts of the building process.

Keywords: Computer Aided Design/Computer Aided Manufacturing (CAD/CAM), Digital Fabrication Tools, Architectural Modeling, Collaborative Design Environments.

ÖZ

MİMARİ MODELİN YENİ BİR EŞPAYLAŞIMLI TASARIM ORTAMI OLARAK MAKİNALARLA AYNI DİLİ KONUŞMASININ YOLU

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Bu çalışma kapsamında bilgisayar destekli tasarım (CAD) ve bilgisayar destekli üretim (CAM) sistemlerinin birbirleri ile nasıl ilişkilendirilmeleri gerektiği ve mimarlık alanı söz konusu olduğunda, mimari modellemenin bilgisayar destekli tasarım/bilgisayar destekli üretim (CAD/CAM) sistemi içinde nasıl ele alınması gerektiği incelenmiştir. Bilgisayar destekli teknolojilerin mimari tasarımla bütünleştirilmesi tasarım-üretim etkileşimi üzerinden araştırılmıştır. Bu araştırma CAD/CAM sürecinin, ilk tasarım aşamasından son ürüne kadar olan aşamalarının bir örnek üzerinden incelenmesini kapsamaktadır. Bir tasarım nesnesi CAD araçlarıyla modellenmiş, ve bu model CAM araçları kullanılarak üretilmiştir. Bu örnek çalışma ile CAD/CAM süreci ve bu sürecin, mimari tasarım ve mimarlığın inşaat/üretim/imalat aşamaları arasındaki ilişkiye getirileri incelenmiştir. Sonuç olarak bu çalışma, mimarlık alanına CAD/CAM sisteminin sunabileceği olanakları göstermiş ve bu sistemin parçaları arasındaki ilişkinin kurulabilmesinde mimari modelleme için nelerin gerekli olduğunu listelemiştir.

Anahtar Kelimeler: Bilgisayar Destekli Tasarım/Bilgisayar Destekli Üretim (CAD/CAM), Sayısal İmalat Araçları, Mimari Modelleme, Eşpaylaşımlı Tasarım Ortamları.

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INTRODUCTION

Computational technologies and digital tools have become essential elements of the modern world. The impact of these revolutionary technologies can be seen in all aspects of life: from simple daily routines to complicated tasks; from social sciences to advanced technologies; from art to medicine, and architecture is no exception to these advances.

Design is usually conceived as the conceptual idea behind a work of art, and the model is usually as the representation of the design idea. However, in the field of architecture model is not only used for representational purposes, but it is also used for many tasks such as exploring design ideas, form finding, space analysis, etc. With the emergence of the computer-aided technologies to the fields of design three-dimensional (3D) digital models have started to be used for various purposes including representation, analysis, and manufacturing. Hence, the model has become a new collaborative design environment in which all the actors can involve in this 'new design processes' through the evolving model.

In the field of architecture, the way a design is conceived, the tools that are used, the way of thinking, all affect the final product, thus the entire construction process. Computer-Aided Design/Computer-Aided Manufacturing (CAD/CAM) technologies offer a medium to the architect with which s/he has the ability to handle the aspects of a project as a whole. Computational technologies bring new potentials to both design and construction processes of building, and digital tools not only provide tools for the design process, but also offer possibilities for collaboration between the architect and the constructor.

Here it should be pointed out that, although, CAD technologies (drafting tools, digital models, etc.) have become essential tools of the architect's office today, their chief role has come to be as 'electronic pencils', taking over from the traditional pencil and paper. At this point the question should be raised as to how computers may be better utilized, specifically not only as a drafting aid, but also in actual architectural design, and in the construction/manufacturing/fabrication at the culmination of the design process.

In the field of architecture, the digital model has the potential to evolve to be the collaborative design environment offering a medium in which the archtitect has the opportunity to communicate with other design participants such as engineers, constructors, clients, etc. In such a collaborative design environment the 3D digital model becomes the main instrument to communicate[1]. Thus, the way the architectural model is conceived and treated is subject to change from being just a representation of the project to being the medium of high collaboration among the various fields of building.

Among the actors of the architectural design process, the 'new role of the digital model' as a base for the manufacturing has been investigated in the study. Hence, throughout the study the 'architectural design' is used in the context of being the digital design model yielding the collaborative environment for all the design actors as in the case of CAM. The term also covers the conceptual design idea

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[1] GÖNENÇ SORGUÇ, Arzu. "Role of System Architecture in Developing New Drafting Tools" in: *Japanese Society of Mechanical Engineers International Journal* (Special Issue: The Latest Frontiers of CAD/CAE/CG, Vol. 28, No. 2, p. 244-250). June 2005.

while being the main instrument of the collaborative design environment in the field of architecture.

Hence, the objective of this study is to inquire as to how Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM) technologies can be utilized in the field of architecture in order to enhance the link between design and construction, and how architectural modeling can be utilized to serve as an interface for the construction/manufacturing/fabrication processes of building.

On the side of the construction/manufacturing/fabrication process, another essential question arises: considering the integration of architectural design together with digital tools, how do these technologies shape the construction process in architecture?

The subject matter briefly defined above is studied first by explaining the motivation and justification behind the study. Then, by exploring CAD/CAM technology and the way it is applied in architecture and other fields, such as aerospace, automotive, etc., further possibilities and potentials of these tools are illustrated. It is also attempted to draw attention to how architectural design and the consequent construction process may benefit from modification.

When the manufacturing processes of architecture within the realm of advanced technologies are considered, it is seen that there are differences between conventional methods and the usage of digital tools and computational technologies. Many disciplines have found and continue to search for ways to adapt themselves to computational technologies. Among these, automotive and aerospace industries are accepted as the fields making the most of computational technologies. In the example of automotive design, the integration of computer-aided technologies and methods in the product development process has helped the sector to shorten development cycles while increasing the level of quality which is certainly a global challenge in the industry[2].

It can be said that architecture, having yet to develop its own applications for these technologies, draws upon the experiences of other disciplines, and what architecture has borrowed is mostly used for representational purposes. It can also be said that unlike other disciplines, architectural design does not much contribute to the construction/manufacturing/fabrication processes.

Architectural design is shaped not only by the creativity of the architect but also by the definition of the design problem, its requirements, and expected qualities, and moreover, by technology in the realization of the proposed design. Aside from the limitations of the design problem and/or program, another limitation in the design work of an architect is the computability and/or the 'manufacturing/ fabrication' of their design. In the realm of this study several questions concerning the integration of computational technologies and architectural design have been searched for. The following questions can be asked in this respect to illustrate the idea behind the study:

a. How can the possibilities of architectural design and construction/ manufacturing/fabrication processes of building be enhanced through the use of computational technologies and digital tools, and what should architects be aware of on the way evolving from architectural model to collaborative architectural design environment?
b. In this respect how can CAD/CAM technology allow collaboration between architects and engineers, or serve as a link between architectural design and the construction/manufacturing/fabrication process of building?

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[2] HUDI, Johann and SPIES, Robert. *Integration of Digital Mock-Up and Multibody Simulation in the Product Development Process*. International ADAMS Users' Conference. Berlin, 1999.

Hence, the fundamental question that should be asked is how can these new technologies, with all their potentials, be efficiently integrated not only into the architectural design process, but also into the construction/manufacturing/ fabrication processes, and how can architects adapt to these processes and benefit from computer-aided technologies and methods?

Today computer-aided technologies are mostly seen as tools to ease the drawing/drafting in architectural design, and to be used for representational purposes. The ability to create realistic images of the design work is seen as the most striking improvement in computational technologies. While the innovations brought to the architectural work by this kind of thinking cannot be denied, computational technologies should not be reduced to being just a means of representation discarding their potential of being the main instrument of design collaboration.

Computer-based information systems allow for the efficient transfer of design information. "The integration of CAD with construction through the exchange of computer-based information systems is becoming an increasingly common aspect of contemporary architectural practice."[3] In the example of the Bilbao Guggeheim Museum of Frank Gehry (Figure 1.1), the interaction between designers and contractors throughout the detailed production process demonstrated the importance of the role of information exchange in the building industry[4].

Advances in analysis, visualization and manufacturing techniques, and the means to permit such complicated exchanges of data now allow the designer and the engineer to construct forms, details and variations that would previously have

[3] SZALAPAJ, Peter. *CAD Principles for Architectural Design: Analytical Approaches to Computational Representation of Architectural Form.* Architectural Press, 2001. (p. 208)

[4] Ibid.

been almost impossible to construct[5]. "Capabilities of the designers increased tremendously letting them to discover geometries other than the Euclidian geometry. New forms that were once very difficult to conceive, develop and represent – and almost impossible to manufacture – are introduced into the designers' terminology."[6]

Figure 1.1 Bilbao Guggenheim Museum[7]

Thus, the aim of this study is to investigate the relationship between architectural modeling and CAD/CAM technology within the realm of collaborative design environment through a case study on the subject. The second chapter begins by providing a history of CAD and CAM technologies through computers to enlighten the way from the very first computer-aided drafting tools through to

[5] THORNTON, John. "Fabrication Research" in: *Architectural Design* (Volume 75, Issue 4, p. 100-103). July/August, 2005.

[6] ÇINGI, Güney. *The Influence of Digital Technologies on the Interaction of Design and Manufacturing Processes*. METU, 2006. (p. 43)

[7] http://en.wikipedia.org/wiki/Guggenheim_Museum_Bilbao (December 2007)

today's advanced technologies. Accordingly, CAD/CAM technology is introduced, the definitions of related terms are given, and the tools and their fields of usage are then indicated.

CAD/CAM technology and its relation to architectural design are illustrated in the third chapter. Architectural and digital modeling techniques, together with their respective effects on design, are investigated. The individual relations both CAD and CAM have with architectural design are researched and attempted to be understood with help of examples.

Based on the findings of the previous chapters, the fourth chapter is devoted to the first phase of the case study. Computer-aided design/drafting environments are tried to be understood. Several modeling techniques are examined within a number of modeling environments, drawing attention to the differences between these environments. In a sequential order, the necessary tools for a digital design and a digital model, together with manufacturing requirements, are investigated.

In the fifth chapter, the manufacturing of a digital design is investigated through the creation of a real object. The entire process, from the digital model to the actual object, is explained in its sequential order, together with the study of necessary tools for the production process and CAM programming. The advantages and disadvantages of CAD/CAM are given drawing on experiences of the case study. Finally, the outcome of the study is documented, and the results are compared so as to understand the CAD/CAM procedure in its entirety.

In the conclusion, the outcome of the study is clarified and summarized together with the observations made throughout the study.

CHAPTER 2

SURVEY OF CAD/CAM TECHNOLOGIES

Asking the question of ‘how many?’ must have started the revolution that would lead to millennia of development along a road that has resulted in the computer. All of the developments that occurred from the invention of the numbers up until today’s digital computers have been based on the need to understand and reshape the universe. It has generally been the military needs of defense and attack that have led the way in the development of tools of high technology, the technologies and by-products of which have gone on to contribute to the well-being of societies, as in the case of computers and computer-based technologies.

The name 'computer', originally meaning the person who made calculations and solved equations, was adopted as the name of a machine in 1940s. Defined as a calculator for complex mathematical problems before the 1970s, ‘computer’ today means a programmable electronic device that can store, retrieve and process data[1].

Computers carry out all their tasks by transforming information into a mathematical language. Calculations within the processor are transferred into the information desired by the user, whether for a game, the modeling of a building,

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[1] CERUZZI, Paul E. *A History of Modern Computing*. The MIT Press, 2003.

or even a picture. As an example, in a computer game the game is actually played with codes and numbers generated and processed by the computer, which makes all the necessary calculations and computations on behalf of the player.

As the tasks carried out by computers today go far beyond merely computation, being used not only for adding or subtracting but for much more complicated tasks in the modern world, the integration of digital tools into our lives to satisfy our needs, from communication to much more detailed engineering tasks has changed the world around us.

Today, there are millions of personal computers around the globe, and their sizes have decreased to laptops and even palmtops, which when installed with the necessary software are capable not only of word processing and accounting, but also many useful tasks related with everyday usage, engineering, designing, manufacturing, and so on. Computer-Aided Design and Computer-Aided Manufacturing (CAD/CAM) technologies are among the most striking developments of these digital renovations.

CAD/CAM technologies make an ever-growing area in the service of many disciplines, including architecture. However, the true worth of CAD/CAM technologies has not been fully discovered in the architectural field. These technological advances have always had an impact on architecture, however, the emergence of CAD/CAM into the field has been steady, and the acceptance of each stage of progress of technology in the profession has taken time. As Brookes et al. states: "Strangely, the building industry seems slow to accept or develop new ideas.[2]"

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[2] BROOKES, Alan J. and POOLE, Dominique. "Introduction" in: *Innovation in Architecture*, (p. 1-14) ed. Alan J. Brookes and Dominique Poole. Spoon Press, New York, 2004. (p. 12)

However, architecture cannot be considered apart from the technological advances of the era in which it is produced. As McCleary states:

> *"More so than other professions, the discipline of architecture struggles with the relative importance of deriving its processes of design and construction from imitations of its past, conventions of the present, or the invention of its future."*[3]

Every new emergence has brought with it a revolution in design consideration, and today computer-aided technologies and methods are changing the way design is considered in the field of architecture. CAD/CAM technologies have the potential to reshape the link between design and construction by digital means.

In order to understand the growth of CAD/CAM technologies, it is necessary to provide a general perspective of CAD and CAM technologies.

2.1 Computer-Aided Technologies

2.1.1 Programming Languages and CAD

The term 'programming' in computers in the modern sense was originated by the team that created the ENIAC (a programmable electronic computer built to calculate firing tables for the U.S. Army), although they used the phrase 'to set up' when describing the configuration of the machine to solve different problems, which actually meant plugging and unplugging a maze of cables and setting arrays of switches[4].

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[3] McCLEARY, Peter. "Innovations in Architectural Technology" in: *Phi Kappa Phi Forum*. (Volume 83, Issue 3, p. 40-43). Summer 2003. (p. 40)

[4] CERUZZI, Paul E. *A History of Modern Computing*. The MIT Press, 2003.

After the first programmable computer, through stored program computers and then into the modern era, the storage and programmability capabilities of such computing machines were improved. The 'Universal Turing Machine', developed by Alan M. Turing in the 1930s[5], worked on the theory that "any stored-program computer can be programmed to act as if it were another machine"[6]. By the writing of algorithms, meaning a finite set of instructions to accomplish a defined task, the stored-program computer would be able to work as an all-purpose computing machine. The mathematical model behind Turing's idea of such a machine is described by Davis (2000) as:

> *"Turing knew that an* algorithm *is typically specified by a list of rules that a* person *can follow in a precise manner… But he shifted his focus from the rules to what the person actually* did *when carrying them out. He was able to show, by a process of successively stripping away in essential details, that such a person could be limited to a few extremely simple basic actions without changing the final outcome of the computation. Turing's next step was to see that the person could be replaced by a machine capable of performing these same basic actions."*[7]

The idea of the stored-program computer and the developments that followed made it possible to store a set of instructions on a tape, which enabled it to be used several times. Today we use software packages written in programming languages that run on operating systems. These translate the information we give to the software into the assembler language, and then into basic machine language, allowing the computer to operate. The procedure is reversed for the operation to

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[5] Ibid.

[6] Ibid. (p. 149)

[7] DAVIS, Martin. *The Universal Computer: the Road from Leibniz to Turing*. W. W. Norton & Company, New York. 2000. (p. 147-148)

be understood by the user, as, for example, a line on an entity-based drafting program, or the image of a model in a rendering program.

Development in software has come a long way, with the programmability and storage capabilities of the computer making it possible to use the computer for countless tasks, from computing to communicating. Also it is now possible to use the computer for highly detailed engineering calculations, creating virtual realities, etc.

Computer-Aided Design (CAD) technology can be considered as being one of the revolutionary developments that computing machines suggested. CAD, in short, means using computer hardware and software in order to carry out the design process. In the modern sense this process is handled by "using sophisticated computer graphics techniques, backed up with computer software packages to aid in the analytical, development, costing, and ergonomic problems associated with the design work"[8].

CAD was firstly used for military applications in the mid-1950s, but it was Ivan Sutherland's introduction of 'Sketchpad' software in his PhD Thesis in 1962 at the Massachusetts Institute of Technology (MIT) which made CAD generally acknowledged[9]. The development of Sketchpad illustrated the new potentials of this medium, such as the ability to create drawings and objects interactively on a television-like CRT (cathode ray tube) produced by MIT in 1950[10].

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[8] HAWKES, Barry. *The CAD/CAM Process*. Pitman Publishing, London, 1994. (p.1)

[9] Ibid.

[10] ZEID, Ibrahim. *CAD/CAM: Theory and Practice*. McGraw Hill Inc. New York, 1991.

Sketchpad can be considered as the ancestor of the modern CAD programs, being a major break-through in the development of computer graphics.[11] "The Sketchpad system makes it possible for a man and a computer to converse rapidly through the medium of line drawings."[12] It was demonstrated with Sketchpad that computer graphics, being the "generation, presentation, and manipulation of models of an object and their different views with the help of a combined form of computer hardware, software and graphic devices"[13], could be utilized for technical and creative purposes.

The development of CAD continued with the evolution in computer graphics, the development of which, alongside various kinds of software with highly structured capabilities, has secured the position of CAD as the main instrument in design processes today. As development never stops, much more can be expected in the future.

In the field of architecture, it can be said that CAD has been adopted as a rapid tool for drafting/drawing and representation. However, the adaptation of architects to the tools of computer graphics has not been immediate. Software applications devoted to architectural design have been developed over the years, offering capabilities to create both two-dimensional drawings and three-dimensional models, and the creation of realistic images of the architect's design.

CAD has also given architecture new prospects for design consideration, and geometric manipulation of design intent has become easier. In the curved glass roof structure of the Sage Gateshead of Foster & Partners, for instance (Figure

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[11] http://en.wikipedia.org/wiki/Sketchpad (December 2007)

[12] SUTHERLAND, Ivan E. *Skethcpad: A Man-Machine Graphical Communication System.* Doctoral thesis submitted at MIT. January, 1963. (p.17)

[13] AMIROUCHE, Farid M. L. *Computer-Aided Design and Manufacturing*. Prentice Hall, New Jersey. 1993. (p. 97)

2.1), the sheltering roof has been created by intersecting of two splines sweeping through each other. Through parametric modeling, the variations in the roof arches have been shaped for construction. Without computer-aided technologies it would have been almost impossible to manipulate the geometry behind the curvature.

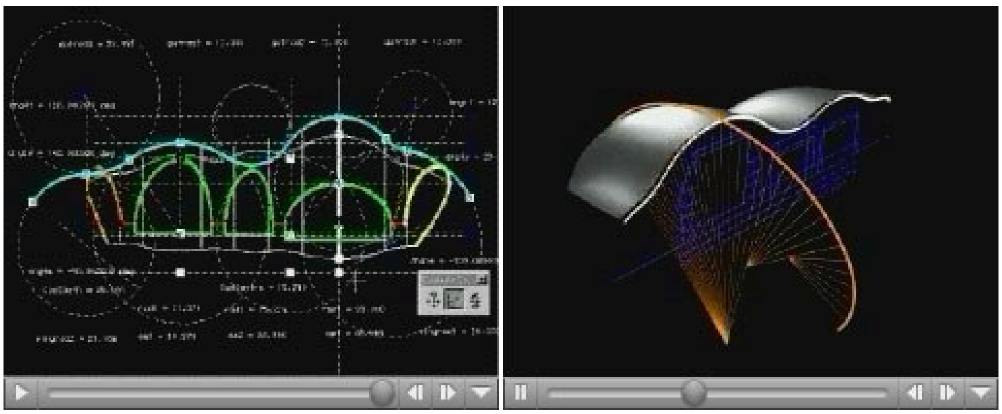

Figure 2.1 Simulated images of the roof structure of the Sage Gateshead.[14]

Another example can be the cladding of the Esplanade – Singapore Art Centre of Michael Wilford and DPA Architects. The form of the concert hall, having a sculpted non-linear surface, and the façade of which made of a space-frame grid of a series of dimensionally equal elements, would have been impossible to design without computer-aided techniques to handle the geometry[15] (Figure 2.2).

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[14] www.fosterandpartners.com (December 2007)

[15] BROOKES, Alan J. and POOLE, Dominique. “Introduction” in: *Innovation in Architecture*, (p. 1-14) ed. Alan J. Brookes and Dominique Poole. Spoon Press, New York, 2004.

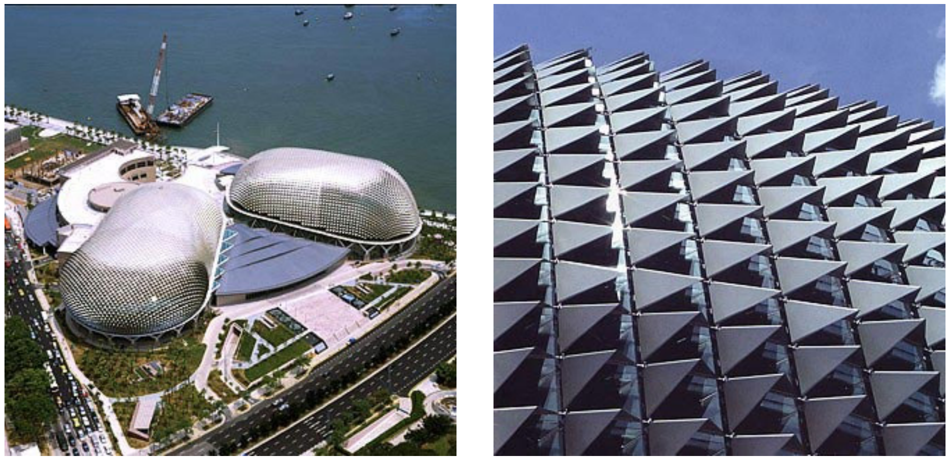

Figure 2.2 The complex roof form of Singapore Art Centre[16].

2.1.2 Machining and CAM

The development of CAD systems and the new potentials for design introduced by CAD systems have also had an impact on manufacturing processes. As long as it is possible to manipulate design geometry with high accuracy, the finished product should be as accurate as the design. CAD technology brought about the need to use Computer-Aided Manufacturing (CAM). CAM describes a set of automated operations. In order to manufacture, the computer is used as an interface to control the appropriate machining process.

The origins of CAM, in fact, lie in the development of numerically-controlled (NC) machining[17], which allowed the control of modified machining tools for metalworking applications[18]. In the 1960s, these techniques began to be controlled by computers, when the term NC turned into CNC (Computer Numerical

[16] www.atelierten.com (January 2008)

[17] HAWKES, Barry. *The CAD/CAM Process*. Pitman Publishing, London, 1994.

[18] CALLICOTT, Nick. *Computer-Aided Manufacture in Architecture: The Pursuit of Novelty*. The Architectural Press, 2001.

Control)[19]. With the developments in automated operations and computer-controlled manufacturing technology the term CAM was adopted for general usage[20].

"The basic idea underlying numerical control technologies can be traced back to the industrial revolution and the use of punched paper cards, tapes, or other devices to control the operations of machines.[21]" It was in 1950s that the first NC milling machines, reading instructions from punched paper tapes, were built[22]. New methods had been sought for the input of instructions alongside the evolution of programming languages for NC machining. The integration of the computer with the NC machining and the evolution of CAM software for writing the numerical control code, controlling machine movements for CNC machining become considerably easier[23].

The development of the microprocessor, and later the personal computer, and the direct marketing of CAM packages, led the way for substantial improvements in the CNC machine tools, and allowed small or medium-sized manufacturing enterprises to add CAM to their manufacturing environment[24]. The increase in the usage of personal computers extended the usage of CAM within non-specialist manufacturing environments.

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[19] HAWKES, Barry. *The CAD/CAM Process*. Pitman Publishing, London, 1994.

[20] Ibid.

[21] SCHODEK, Daniel; BECHTHOLD, Martin; GRIGGS, Kimo; KAO, Kenneth Martin and STEINBERG, Marco. *Digital Design and Manufacturing: CAD/CAM Applications in Architecture and Design.* John Wiley & Sons, INC. 2005. (p.24)

[22] GIBBS, William F. "The History of CAM Helps Predict its Future" in: *Computers in Manufacturing* (p. 34-38). July 1999.

[23] Op. cit.

[24] CALLICOTT, Nick. *Computer-Aided Manufacture in Architecture: The Pursuit of Novelty*. The Architectural Press, 2001.

Rapid prototyping (RP) and computer-aided manufacturing (CAM) facilitated the production of small-scale models and full-scale building components directly from 3D digital models[25]. Mass customization, i.e. to mass-produce irregular building components with the same ease as standardized parts, was also introduced to the field of construction[26]. It can be said that the link that computer-aided technologies created between design and production narrowed the gap between the two main components of building industry.

2.1.3 CAD/CAM – Integration of Digital Technologies with the Field of Production

When CAM was introduced to the field of design and CAD to the field of production, new dimensions in both fields were exposed. Computer-Aided Design/Computer-Aided Manufacturing (CAD/CAM), being "the integration of computers into the production process to improve productivity"[27], was born. As the production information could be created and recreated with CAD, CAM techniques have become easily accessible and easily applicable. Previously, a specialist programming knowledge had been required, but with the emergence of CAD, and the software developed in parallel, designers and production engineers were now able to generate models for the production of their designs.

The CAD/CAM philosophy came into existence with the development of computer-aided CNC programming techniques and languages, when it became apparent that data exchange was possible between CAD and CAM systems[28].

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[25] KOLAREVIC, Branko. "Digital Fabrication: Manufacturing Architecture in the Information Age" in: *ACADIA* (p. 268-277). 2001.

[26] Ibid.

[27] BLAUTH, Robert E. "What is CAD/CAM?" in: *The CAD/CAM Handbook,* (p. 5-8) ed. Carl Machover and Robert E. Blauth. Computervision Corporation Bedford, Massachusetts, 1980. (p.5)

[28] HAWKES, Barry. *The CAD/CAM Process*. Pitman Publishing, London, 1994.

Throughout the 1950s and 1960s the developments in interactive computer graphics led the way to the development in CAD/CAM[29]. From the late 1970s and throughout the 1980s various industries, such as aerospace and automotive, realized the potentials of CAD/CAM technologies, and demands for new designs and manufacturing applications responded to successfully within the limited availabilities of the time[30].

Within a cycle of development, computer-aided applications influence one another. The development in CAD/CAM technology has gone hand in hand with the individual evolutions in the techniques of CAD and CAM. The integration of digital technologies with the field of design and production brought universal changes to many industries, such as aerospace, automotive, textile, and so on.

In the field of architecture, a number of noteworthy changes can be seen in the production. The continuous triangulated skin of 30 St Mary Axe of Foster & Partners is a significant example on this respect (Figure 2.3). The glass façade, thus the form of the building follows a true progressive curve with no single radius or centre and is made up of numerous different but regular arcs all joined together[31]. By the aid of computer-based techniques the cladding systems for 30 St Mary Axe were designed and manufactured accordingly, as the entire process of production for the building was computer-controlled[32].

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[29] ZEID, Ibrahim. *CAD/CAM: Theory and Practice*. McGraw Hill Inc. New York, 1991.

[30] Ibid.

[31] ABEL, Chris. *Architecture, Technology, and Process*. Architectural Press, Oxford, 2004.

[32] Ibid.

Figure 2.3 Triangulated façade of 30 St Mary Axe.[33]

2.2 CAD/CAM

2.2.1 CAD/CAM Tools

CAD/CAM technologies have led to the development of a number of systems to support various design and production/fabrication activities. CAD/CAM, being a whole system that starts with the digital design and culminates in the end product, has three major components, as described by Schodek et al.[34]:

[33] www.fosterandpartners.com (January 2008)

[34] SCHODEK, Daniel; BECHTHOLD, Martin; GRIGGS, Kimo; KAO, Kenneth Martin and STEINBERG, Marco. *Digital Design and Manufacturing: CAD/CAM Applications in Architecture and Design.* John Wiley & Sons, INC. 2005.

Digital interactive design and analysis environment (a CAD system)

The digital geometric modeling of the object is to be eventually produced. The system includes computer hardware and software. These digital environments have advanced surface and solid modeling capabilities.

Computer-aided manufacturing software (a CAM system)

The system permits the user to specify how the digitally designed model is to be manufactured. The user creates a series of digital instructions to control specific machines.

One or more numerically controlled machines (CNC)

These are the machines that translate digital instructions into actual machine operations in order to make the object.

By providing the basic interactive design capabilities, a 'digitally based computer-aided design system' is the most fundamental part of a complete CAD/CAM system[35]. Not all of the digital design environments are the same in the way they support manufacturing and/or assembly processes. Each has special properties, for example, some are for creating photo-realistic images and/or animations, which do not usually support manufacturing needs, making it essential to define the kind of digital model so that it is well-defined for manufacturing/analysis and/or design purposes[36].

Some digital modeling systems also support CAM functions in their CAM modules, providing digital instructions for the specific machining within the same environment. There are also other stand-alone packages to create instructions for machining. It is critical here to decide on the CAD and CAM environments, as the

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[35] Ibid.

[36] Ibid.

collaboration between the design and production method is essential in order to accomplish the design needs.

CAM environments include rapid manufacturing (RM, widely known as rapid prototyping (RP)) and CNC machines. The basic difference between these two types of production is that RP processes create objects by additive methods (building up the model layer by layer) and CNC processes by subtractive method (removing material from the model)[37]. RP processes include 3D printing, stereolithography, and fused-deposition modeling, while CNC processes include milling, water-jet cutting, and laser cutting[38]. Each of these methods vary in the way they produce the object, the material used, etc. and usually need varying design and numerical control instruction methods. As the system should be considered as a whole with all of its components, the design and manufacturing process that follows the design have to be in collaboration with each other.

The modeling environment, the commands and methods of modeling within the environment and the type of model affect the production processes, and CAM programming is also important in that sense. The type of CNC machine, and thus the type of production should be decided upon in the early stages of the design process, prior to the manufacturing phase, in order to ensure an appropriate machining process for the model. When CAM programming is done properly, then the tool path is verified and is simulated for control. Later it is post-processed to the machine for production. This process of CAD/CAM will be explained in detail in the following chapters.

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[37] SEELY, Jennifer CK. *Digital Fabrication in the Architectural Design Process*. Bachelor of Architecture, University of Arizona. May 2000.

[38] Ibid.

2.2.2 CAD/CAM Usage in the Professional Field

The use of CAD/CAM technologies in architecture and other fields of design opened up new design vocabularies, and the CAD/CAM system is developed according to specific industry needs[39]. Production processes based on CAD/CAM technologies are widely used in the product design, automotive, aerospace and shipbuilding industries, in which the impact of the adoption of innovative technologies has been profound[40]. "Today, various appliances, cars, airplanes and ships are entirely designed, developed, analyzed and tested in a digital environment, and are then manufactured using digitally-driven technologies.[41]"

Being adopted at first as rapid drawing/drafting tools, computer-aided technologies are there to satisfy architectural design needs of geometric manipulation, surface generation, design consideration, etc. The field of architecture has also been affected by the impact of CAD/CAM technologies. The opportunities for the field of architecture, engineering and construction industries are no different than the advancements in other fields listed above.

2.2.3 Effects of CAD/CAM Usage

In order to exploit the potentials of CAD/CAM technologies to the maximum extent there are some aspects to be considered that have not previously featured in the design process, and there is a specific vocabulary that is needed to be learned.

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[39] SCHODEK, Daniel; BECHTHOLD, Martin; GRIGGS, Kimo; KAO, Kenneth Martin and STEINBERG, Marco. *Digital Design and Manufacturing: CAD/CAM Applications in Architecture and Design.* John Wiley & Sons, INC. 2005.

[40] KOLAREVIC, Branko. "Introduction" in: *Architecture in the Digital Age – Design and Manufacturing,* (p. 2-10) ed. Branko Kolarevic. Taylor Francis, 2005.

[41] Ibid. (p. 10)

The CAD/CAM procedure begins with the computer model (digital design) and ends up with a product. For the steps in-between, the CAD/CAM system must be exactly told what to do, which necessitates that the complex geometry must precisely be specified in a numerically based language that the machine control system can understand.[42] The disadvantage for the designer has been that s/he needs to learn how to handle the geometry in its complexity, but the need for a system that allows highly complex shapes to be exactly produced has been one of the driving forces behind the development of these systems.[43] As put forward by Penttila, there is a belief that:

> *"CAD-systems' evolution has followed the needs of the designing community so well, that one might even claim, that CAD has not affected the design quality nor the architectural forms but, merely the architectural needs from design practice have strongly affected CAD-systems' evolution."*[44]

In one way or another, CAD/CAM systems are being developed day by day. For the architect there is much to learn before being able to garner adequate efficiency from the systems; but the potentials of the CAD/CAM technologies cannot be ignored.

In the aerospace industry, for example, the usage of these digital environments has increased the speed of production up with fully precise manufacturing possibilities and availabilities of design. With the emergence of the digital mock-up, the digital

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[42] SCHODEK, Daniel; BECHTHOLD, Martin; GRIGGS, Kimo; KAO, Kenneth Martin and STEINBERG, Marco. *Digital Design and Manufacturing: CAD/CAM Applications in Architecture and Design.* John Wiley & Sons, INC. 2005.

[43] Ibid.

[44] PENTTILA, Hannu. "Describing the Changes in Architectural Information Technology to Undestand Design Complexity and Free-Form Arhitectural Expression" in: *ITcon* (volume 11, special issue, p. 395-408). 2006. (p. 399)

model can now be used for analysis and tests rather than the physical prototype. Similar digital production can be seen in "the concept of Building Information Modeling (BIM) which is to build a building virtually, prior to building physically, in order to work out problems, and simulate and analyze potential impacts."[45]

The emergence of CAD/CAM technologies in the field of architecture is an area that requires investigation in order to understand the possible outcomes of the integration of the two fields. The architectural design process, and later the construction processes in the creation of a building should be considered within the realm of CAD/CAM technologies. The next chapter illustrates CAD/CAM technology, along with its properties and effects on architectural design and thus, the construction processes of architecture following the design processes.

[45] SMITH, Deke. "An Introduction to Building Information Modeling (BIM)" in: *Journal of Building Information Modeling* (Issue 1, p. 12-14). Fall 2007. (p. 12)

CHAPTER 3

THE INTEGRATION OF ARCHITECTURAL DESIGN AND ARCHITECTURAL MODELING WITH CAD/CAM TECHNOLOGIES

> "*The use of computer-aided design and manufacturing (CAD/CAM) technologies in architecture and design is no longer simply an exciting but still emerging interest area*"[1].

It can be said that architecture has sought for innovatory design schemes and ideas together with new and complex forms throughout the history. The fascination of building large-scale complexly-shaped forms demands that the architect/designer should adapt to appropriate ways of construction. Before the advent of CAD in 1960s, and the acceptance of it in the field of architecture in 1980s, architects examined curved and complex shapes to address complicated function and space constraints and designed buildings having complex geometries. However, in order to construct the designs, expensive construction techniques had to be used, often

[1] SCHODEK, Daniel; BECHTHOLD, Martin; GRIGGS, Kimo; KAO, Kenneth Martin and STEINBERG, Marco. *Digital Design and Manufacturing: CAD/CAM Applications in Architecture and Design.* John Wiley & Sons, INC. 2005. (p. 3)

relying on trial and error, and in some cases the construction had to undergo rebuilding several times[2].

The emergence of digital technologies in the field of architecture eased the communications between the architect and the craftsmen. In some early complex examples, such as Antoni Gaudi's Sagrada Familia Church in Barcelona (Figure 3.1), architects experienced difficulties in expressing their ideas and communicating with other disciplines involved in the construction process. For the Sagrada Familia, Gaudi developed a set of rules to be followed for the construction so that the craftsmen could understand and construct the design without the direct supervision of Gaudi[3]. Based on the building technology available in the early 1900s, the construction work for such a detailed and complex design of Gaudi's could have taken several hundred years. Today CAD/CAM technologies have been used to speed up the construction of the building, which is intended to be completed around the 2020s.[4]

Early CAD systems had limited drafting capabilities, allowing only 2D and some simple 3D drawings that were only suitable for visualization, documentation and presentation. The technological advances in computer systems enhanced the drawing and modeling capabilities of these environments. Developments in drawing technologies (CAD) alongside the developments in numerically controlled machines (CAM) have occurred simultaneously and have had a marked affect on each other. With the advent of computer-aided techniques, it has become obvious that complex structures are now easier to build than ever. Today, with

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[2] PENTTILA, Hannu. "Describing the Changes in Architectural Information Technology to Undestand Design Complexity and Free-Form Arhitectural Expression" in: *ITcon* (volume 11, special issue, p. 395-408). 2006.

[3] SCHODEK, Daniel; BECHTHOLD, Martin; GRIGGS, Kimo; KAO, Kenneth Martin and STEINBERG, Marco. *Digital Design and Manufacturing: CAD/CAM Applications in Architecture and Design.* John Wiley & Sons, INC. 2005.

[4] http://en.wikipedia.org/wiki/Sagrada_familia (December 2007)

developments in computational technologies, both in hardware and software, digital modeling has gone one step further and become a method for design. With CAD/CAM the 3D digital model stands at the centre of all the processes related to design, and has the potential to be used for a variety of purposes from being the representation of a design idea to making the base for the analysis and manufacturing issues of production.

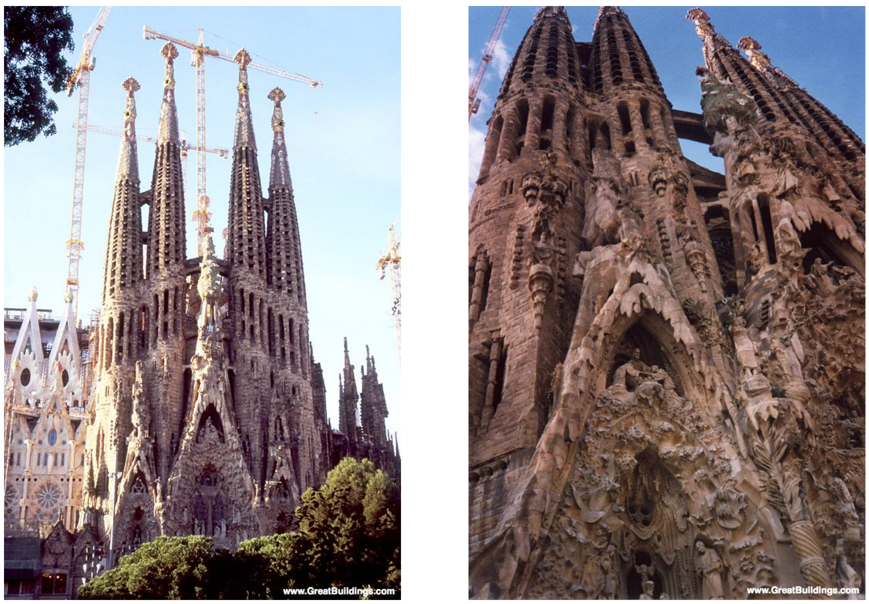

Figure 3.1 Complex design of Sagrada Familia Church[5]

Computation in design also allows many modeling aspects that were not previously possible. CAD/CAM technology, the integration of design together with the capabilities of manufacturing, brings possibilities for simulation in the design and manufacturing processes. With parametric modeling, it is now possible to explore many different geometric and dimensional configurations of a design

[5] http://www.greatbuildings.com/buildings/Sagrada_Familia.html (January 2008)

based on initially defined constraints[6]. The emergence of new materials and construction methods allow the construction of forms that were once close to impossible. The transformation in the modeling techniques of architectural design should be considered together with the new advances of technology and the integration of CAM to the field.

3.1 Architectural Design and CAD

3.1.1 What is Architectural Modeling?

Being the architect's most powerful tool for exploring his/her ideas, modeling – how it is to be done – has, since the very earliest times, had a strong effect on the form, not only as a way for exploring form but also for visualization and representation purposes. Although it was not until the 1920s that architectural modeling became a part of architectural education[7], its role in design was, and still is, inseparable from the way architectural projects are done. Making of models, whether they are sketch models, highly detailed scale models or computational models, takes architecture one step further, since models are tools for the architect to explore and find solutions for form finding, space analysis, user-building interaction analysis, etc. Also each different type of modeling provides different information to the architect that can take the project in many different directions, as any possible information that can be taken from any different modeling type varies.

Digital models, being used first as tools for visualization, have today become an essential part of the design process and serve architects in several different ways.

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[6] SCHODEK, Daniel; BECHTHOLD, Martin; GRIGGS, Kimo; KAO, Kenneth Martin and STEINBERG, Marco. *Digital Design and Manufacturing: CAD/CAM Applications in Architecture and Design.* John Wiley & Sons, INC. 2005.

[7] MILLS, Criss. *Designing with Models: A Studio Guide to Making and Using Architectural design Models.* John Wiley & Sons, 2005.

Besides the ease they bring to manipulating complex geometries, digital models also provide the means to analyze the building and its components at various scales, and become a medium in which different disciplines can meet. The 3D digital model has become the main instrument in design collaboration, and with the evolving role of the model through computer-aided technologies it has come to be the actual design.

3.1.2 Modeling for Manufacturing

When manufacturing processes are considered, models have turned out to be more important defining the construction methods and strategies, precisions, material and labor supply, costs and many more. The role of the architectural model is more emphasized in digital medium together with information technologies. Today, architectural models are not the end product of the architectural design, but they become a collaborative design environment allowing other disciplines to involve in the whole design process. This fact can simply be explained by the diagram given in Figure 3.2, which is true for all computation tasks.

'Real problems' are usually very complex and mostly ill-defined when the number of the variables and parameters are considered. Hence, they need to be simplified and the mathematical models are created based on these simplifications. The complexity of the mathematical model, its precisions, solution methods etc. do not only depend on the skills and knowledge of the designer/researcher but also on the tools (mostly computational and numerical) to be used in the solution of the mathematical model which results in the computational model.

Architectural models are actually representations of very complex real problems and in that sense they are simplified models. When these models are produced in the digital environment, they become mathematical models as well, which consist of set of data related to form, materials, dimensions and relations. Hence, they can be computed regarding to different requirements from analysis to simulations and also for manufacturing/fabrication. Thus, architectural model has evolved to be a new design environment. In this thesis, the term 'architectural design' has been employed in this context throughout the study. In the following part this scheme is explained for architectural model and CAM in detail to emphasize the motive of the present study.

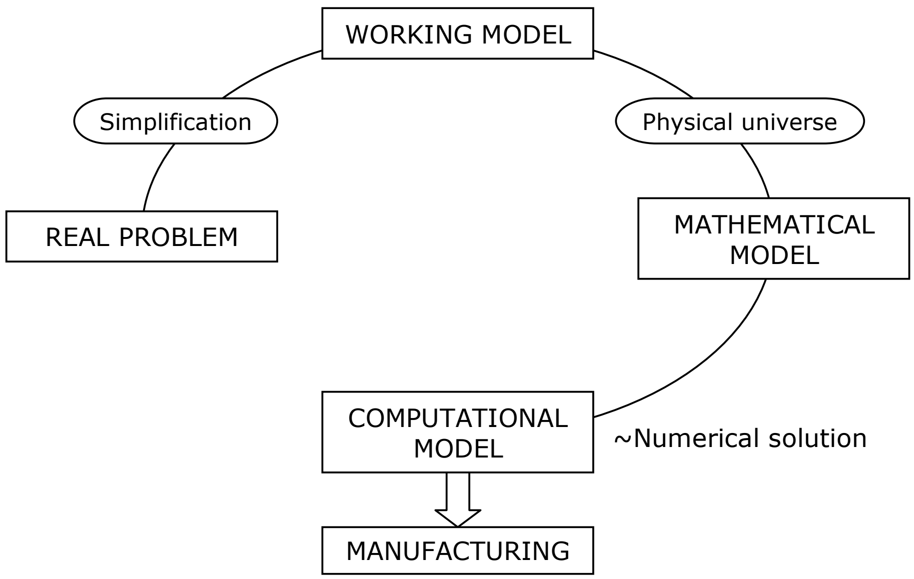


Figure 3.2 Simplified computation cycle of modeling processes for manufacturing[8].

The process of modeling for manufacturing can be summarized beginning with setting the aspects of the design problem in order to acquire a working model of the design problem. Working models can be considered as the sum of the conceptual design with the actual requirements of the design problem that are set previously. Representation and sketch models can be used to visualize the conceptual design and thus, the working model for manufacturing.

[8] Drawn by the author based on the disccusions with the thesis supervisor.

Working models are shaped by the definition of the design problem and its requirements; therefore they are somewhat a simplified model for the real problem of design when manufacturing needs are considered. When in a general term the laws of the physical universe or the physical properties and/or limitations of the design problem are attached to the working model acquired from the design problem, there can be obtained the mathematical model of the manufacturing needs. Mathematical models contain the required data for structural and physical constraints and requirements of the design, and they are especially used to identify the structure, thus the model.

For the manufacturing needs of the design, the mathematical models are used to create the computational models. The model data derived from the mathematical model are utilized for machining, which means together with the mathematical model data, computational models include the machining data for the manufacturing processes.

The computational model illustrates the digital model that is programmed for machining. The cycle is completed when numerical data obtained from the computational model is post-processed for machining operations. It should again be pointed out that computational modeling cycle that has been described above can be attached to any computational operation including the architectural design and subsequent processes of manufacturing related to architectural design. In the following chapters such a cycle of manufacturing process of a design object will be studied.

3.1.3 CAD Models – Properties and Relation with CAM

After the development of the first CAD, which was Ivan Sutherland's Sketchpad in the 1960s, rapid developments in technology resulted in the emergence of new software, and thus new modeling and analysis techniques, as well as new techniques for manufacturing and fabrication. These advances forced architects to re-think the whole design process. Architectural design has evolved to become a medium in which the whole design and construction/manufacturing process, and even the life cycle of the end design, can be explored[9]. Architecture, being a field in which design and construction/manufacturing are so much integrated, began using these technologies initially as drafting aids, then for visualization purposes, and today as a design aid.

Today architects use models mainly for visualization and representation of the design. The architect, using the tools of physical modeling, is faced with several aspects that need to be decided. Choosing the scale, the materials or the medium; and the degree of detail necessary for the purpose of the model; and allowing other disciplines to make further analysis are some of the features that should be included in models. Even with computational modeling these aspects are valid, but the architect has the opportunity to experience the entire design process, as well as the end product, by changing the parameters and design features, being able to decide on and test the materials and construction techniques for the manufacturing of the design. The digital model stands as the basis for the analysis and engineering studies and works of the architectural process, which means the model is not only the representation of the design but has the potential to design the design process and other following processes.

There are different modeling techniques in CAD applications that enable the architect to use the computer as a design tool. When it is intended to realize a model through CAD/CAM, then the choice of the CAD and CAM applications becomes critical. As some available software can only be used for visualization, the decisions concerning the CAD applications and modeling techniques should be given at the outset of the design process. In the hands of a trained architect,

[9] GÖNENÇ SORGUÇ, Arzu. "Role of System Architecture in Developing New Drafting Tools" in: *Japanese Society of Mechanical Engineers International Journal* (Special Issue: The Latest Frontiers of CAD/CAE/CG, Vol. 28, No. 2, p. 244-250). June 2005.

with knowledge of how CAD and CAM should be considered together and how these two systems can be made compatible, computational modeling can serve as a powerful aid to architectural practice.

In this research it is intended to exemplify the process of CAD/CAM through digital modeling techniques and their properties concerning the manufacturing processes. Being one of the actors in the system, the digital model's role as a base for the manufacturing of the design has been investigated in the study. Hence, the type of CAD applications, CAD modeling techniques and ways of modeling should be analyzed prior to modeling for manufacturing.

CAD Modeling Techniques

In various CAD applications the techniques used to model an object have similarities. Among the basic modeling types in CAD there are four types of modeling techniques, which are two-dimensional drawing, wire-frame, surface and solid modeling. Each of these offers different capabilities to the design and the designer according to their way of creating the model. The definitions and special properties of these four modeling types are as follows:

Two-Dimensional (2D) Drawing

This is drawing the projection of an object using points and lines on a plane.

Wire-frame modeling

In this type of modeling the objects are created using simple points and lines. Line segments outline the basic edges of a volume, which makes it more difficult to create curved objects as they need to be defined by linear segments. As the wire-frame model lacks any data regarding faces between lines, it is difficult to differentiate the physical properties of the objects as seen in Figure 3.3.

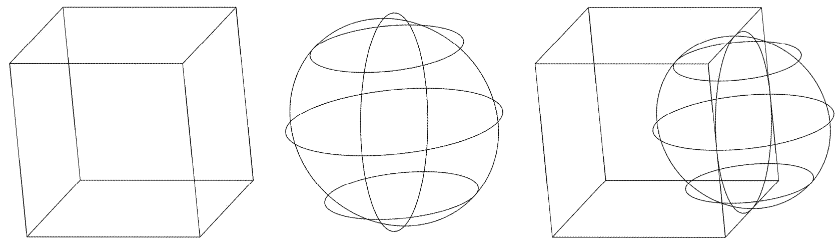


Figure 3.3 Wire-frame models of a cube, a sphere and an intersecting model of a cube and a sphere.

Constructing wire-frame models is relatively simpler when compared to other modeling types, but yet they provide accurate information about the location of a surface discontinuity on an object. Their major disadvantage is their deficiency in providing a complete description of the objects[10]. Thus, wire-frame geometry is of limited value as a basis for manufacture or analysis. The limitations of wire-frame models can be listed as follows[11]:

a. *Ambiguity:* Having no perception of solid shape, it is not possible to distinguish between visible and hidden edges.
b. *Inability to recognize curved profiles:* Longitudinal profiles of cylindrical shapes are not fixed edges between defined points in space. They are seen by the observer as the silhouette of a component face, which could vary in position, depending on the direction of view.
c. *Inability to detect interference between components:* Since the wire-frame model has no knowledge of surface faces, there can be no provision for the automatic detection of unwanted contacts between the object surfaces.

[10] AMIROUCHE, Farid M. L. *Computer-Aided Design and Manufacturing*. Prentice Hall, New Jersey. 1993.

[11] HAWKES, Barry. The CAD/CAM Process. Pitman Publishing, London, 1994.

d. *Difficulty in calculating physical properties:* The correct shape, and therefore the volume, of anything other than very basic components cannot be determined accurately.
e. *No facility for automatic shading:* Color tone variations and shadow effects are applied on surfaces, not on edges, and so cannot be applied to wire-frame models.

Surface modeling

In this type of modeling, space is enclosed by surfaces which can be created and manipulated in various ways. The focus for modeling is on the surface definition/qualities of the 3D object. Different from wire-frame modeling, here not only the geometry of the edges, but all the geometries of the surfaces are defined. Surface modeling, being more versatile, is a higher-level than wire-frame modeling, and its particular advantages over wire-frame include[12]:

a. Ability to recognize and display complex curved profiles.
b. Ability to recognize faces, and thus provide the facility of shaded surfaces in 3D.
c. Ability to recognize facial features, such as holes.
d. Ability to display superior tool-path simulations in 3D for multi-axial machining operations and complex shapes, with ease of a CNC (computer numerical control) manufacture interface.
e. Improved facility for simulation of robot handling.

With the help of surface modeling, it is possible to achieve striking visual representations. Surface modeling has enabled the architect to create new design vocabularies and create freely-formed shapes (Figure 3.4). However, the accuracy of the object has to be clearly identified. It is possible in surface modeling to

[12] Ibid.

create objects on the screen without having geometrical/numerical accuracy, yet giving a visually correct impression. This may not be a problem for visual purposes, but when CAM is concerned, an object has to be defined with high precision in a numerical sense in order to be produced.

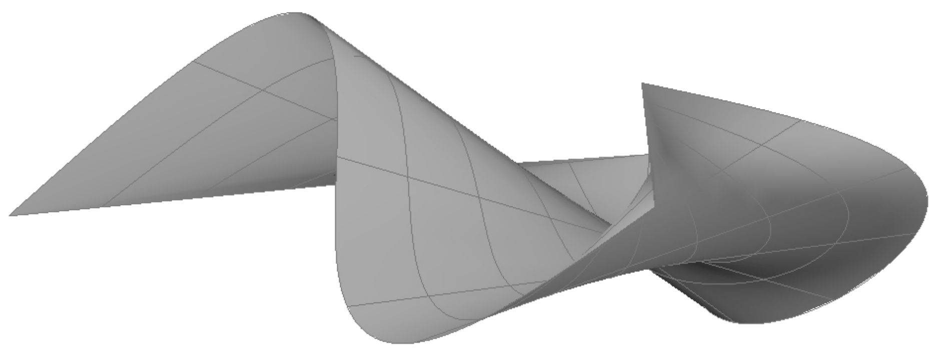


Figure 3.4 An example of a surface mesh.

Surface modeling is usually used in conjunction with solid models, allowing the modeling of more complex shapes that cannot be achieved by solid modeling. Despite the many attributes and advantages of surface modeling, there remain a number of limitations which can only be overcome with the use of solid models. These include[13]:

a. No comprehension of solid volume, with resulting ambiguities.
b. Some surface models give unreliable volume data, depending on the accuracy of the surface definition.
c. Hidden lines cannot be easily removed, nor internal sections easily displayed.

[13] Ibid.

Solid modeling

In solid modeling, objects are created with their volumetric definitions. Complex curved lines and bounding surfaces that define model configurations are numerically defined in a precise way. With solid modeling it is also possible to calculate such properties as volume/mass/center of gravity of the object. When a model provides a complete definition of its volumetric shape, the limitations of wire-frame or surface modeling techniques are overcome. Therefore, solid modeling techniques are mostly used for CAD/CAM applications and CNC machining. The advantages related to solid modeling can be listed as follows[14]:

a. Complete definition of the volumetric shape, and the possibility to distinguish between the inside and the outside of the object.
b. Ability to provide automatic removal of hidden lines.
c. Ability to provide clear 3D section views through components.
d. Analytical advantages, including the display of mass properties and construction of finite elements.
e. Ability to incorporate color choice and tone control.
f. Simulation of mechanism dynamics, tool-path procedures, and robot handling.

There are several ways of modeling in CAD applications to create wire-frame, surface and solid models. In order to create 3D objects, the first possible way is to use the previously defined 3D objects in object libraries of the applications. These libraries usually include basic shapes, such as prism, sphere, cylinder, etc. According to the type of the application, the model type of these shapes may vary, as they may be wire-frame, surface or solid models. The library objects can be modified on their edges, nodes and faces (Figure 3.5) depending on the allowances of the applications. Basic geometrical operations of ***Move, Rotate*** and

[14] Ibid.

Scale are applied on these parts of the shapes in order to acquire topologically similar objects. For example, it is possible to model an apple by modifying the parts of a sphere shape in the library.

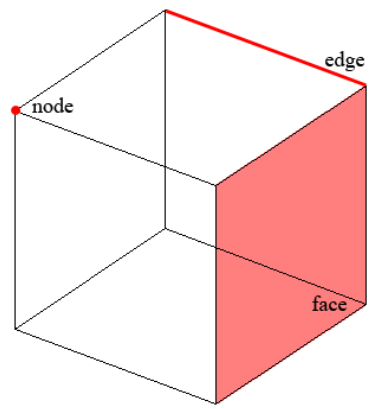


Figure 3.5 Node, edge and face of a cube shape.

Another way to create 3D objects in CAD applications is using the modeling commands on 2D entities in order to acquire 3D models. Similar to the library objects these 3D models may also be modified on their nodes, edges and faces, and be a wire-frame, surface or a solid model according to the type and allowances of the applications. There are three basic type of modeling in this respect among the numerous commands offered by CAD applications. Although their names and the types of model they create may vary in different applications, these three basic commands are ***Extrude, Revolve*** and ***Loft***. The basic working principles of these commands are as follows:

Extrude

In general the extrude command is used to add thickness to a 2D object to create a 3D model. When the 2D object chosen to extrude is an open-ended line, spline or polyline, then the extruded shape is a surface model, but if the object chosen is a closed polyline, it creates a filled volume when extruded. This property can differ in various applications; for example, the closed polyline can only be extruded along the edges without filling a volume. The extruded object is then a closed surface model, i.e. a *visually* closed volume. Although there exists such a discrepancy between applications, the extrude command is generally used to create volumes. The command can also be used to extrude an object along a path, which can be a straight, curved, segmented, open-ended or closed line/polyline (Figure 3.6).

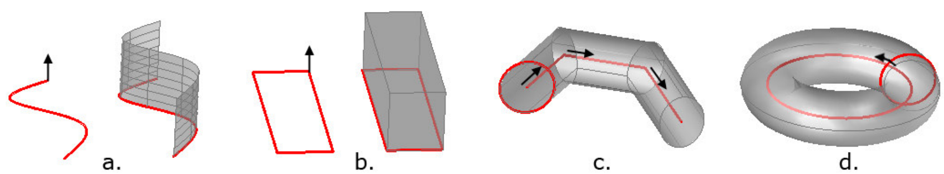


Figure 3.6 Types of extrusion: (a.) Extrusion of a curved line, (b.) Extrusion of a closed polyline, (c.) Extrusion along an open-ended and segmented polyline path, (d.) Extrusion along a closed polyline.

Revolve

In general the revolve command is used to create 3D models by rotating a 2D object around an axis. The revolution occurs along a circular path. However, according to the allowances of the command in the applications, the circular path may be defined as n-sided polygons; n being a previously defined value in the software. The revolution angle can also be specified between 0°-360°. It is possible in most of the software to revolve both open and closed 2D polylines. According to the allowances of the command and the software, in every case if the revolved object is an open-ended object then the revolved 3D shape is a surface model. When the revolved 2D object is a closed polyline, the obtained 3D shape can either be a surface or a solid model (Figure 3.7).

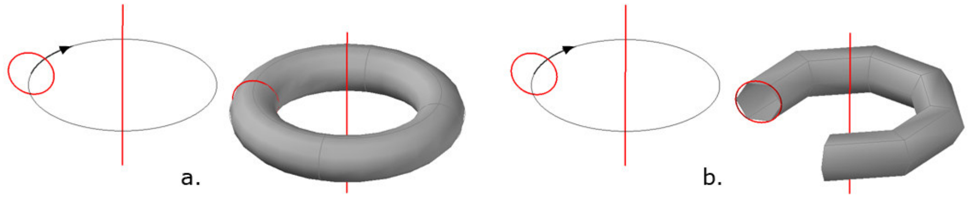


Figure 3.7 Types of revolve: (a.) Revolve command around 360° (b.) Revolve command around 270° along a 6-sided polygon path.

Loft

In general the loft command is used to fill between two or more 2D objects with a surface in space or a solid. If two or more open ended lines are lofted, the resulting 3D shape is a surface. The loft command creates solid models if the lofted 2D objects are closed polylines. This property may also vary, similar to the other two commands, as the 3D objects can either be surface or solid models (Figure 3.8). The loft command, similar to the extrude command, can also be used along a defined path.

In Table 3.1 the basic modeling methods that have been described are listed.

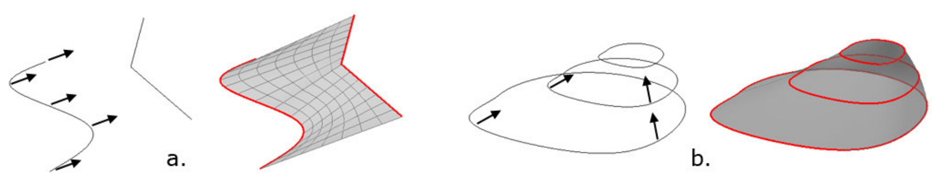
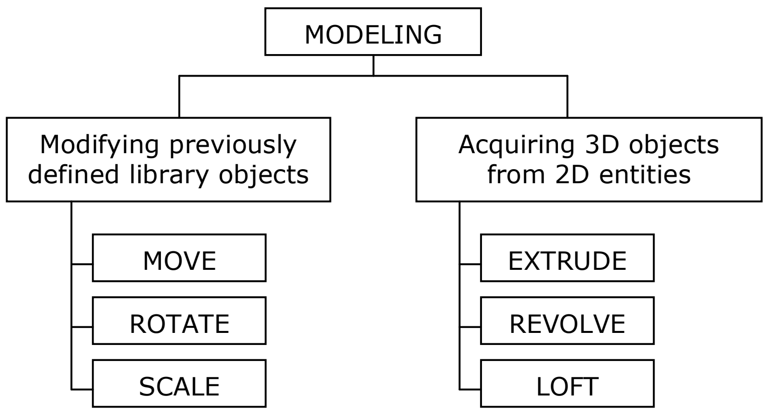


Figure 3.8 Types of lofted shapes: (a.) Lofted surface of a spline and a polyline (b.) Lofted solid of closed splines.

The modeling techniques, the type of the model created, the commands and their ways of usage are important aspects when CAD/CAM systems are concerned. Among the numerous options that applications have for modeling, it is important to differentiate the model type, as for CAM the modeled objects have to be well-defined volumes. Thus, the modeling environment, the commands and what they create have to be well-known to be able to use the digital model as a basis for production.

Table 3.1 Basic modeling methods



3.2 Architectural Design and CAM

Model making has served as an intermediary between complex design ideas and construction workers for hundreds of years. Today, digital model making undertakes the same basic role and gives the opportunities not only for the creation of complex forms, but also for serving as an intermediary between design and construction[15].

When CNC (computer numerically control) devices and the set of technologies known as rapid prototyping (RP) were introduced to the field of manufacturing, it became necessary to allow information exchange between CAD applications and

[15]SASS, Larry and OXMAN, Rivka. "Materializing Design: the Implications of Rapid Prototyping in Digital Design" in: *Design Studies* (volume 27, issue 3, p. 325-335). May 2006.

CAM devices. The development in computer technologies made it possible to give material representation/information to the computer model, and CAM machining is now able to change the model information into the real product.

The procedure begins with the selection of the correct software and CAD/CAM devices to suit the design needs. The model and the material information are essential for production. Surface or solid modeling techniques, their available commands and the manufacturing capabilities of a RP/CNC machine should be known and decided upon beforehand, as Kolarevic states "computationally possible also means that their construction is attainable by means of CNC fabrication processes"[16]. When the model is complete, and the necessary production information applied to it, the information is post-processed, in the relevant software to the CAM machine, which will produce the object accordingly.

3.3 CAD/CAM in Architectural Practice

3.3.1 Various Applications of CAD/CAM

Chaszar states that the features, related to the use of CAD/CAM in fields other than architecture that most inspire architects as follows[17]:

a. *Visualization:* The ability to present graphical information realistically.
b. *Computation:* The ability to perform numerical and text operations with high speed

[16]KOLAREVIC, Branko. "Digital Production" in: *Architecture in the Digital Age – Design and Manufacturing,* (p. 29-54) ed. Branko Kolarevic. Taylor Francis, 2005.

[17]CHASZAR, André. "Blurring the Lines: An Exploration of Current CAD/CAM Techniques" in: *Blurring the Lines,* (p. 6-15) ed. André Chaszar. Wiley Academy, 2006.

c. *Geometric Manipulation:* The ability to deal with forms of great complexity.
d. *Standardization:* The ability to communicate data from one instance to the other, allowing repetition of a design solution.
e. *Rationalization:* The ability to make explicit and editable decisions leading to particular design solutions.

Beyond being electronic pencils for drawing requirements of the architect, CAD/CAM is used for both analysis and manufacturing purposes. The ability of CAD/CAM in the analyzing of complex forms and form-generating options is used to develop complex design solutions. As it can be said that design complexity is related to the number of decisions to be taken, within the whole CAD/CAM system construction complexity can be reduced to the number of fabrication and assembly processes[18]. However, for the CAD/CAM system to work reliably, it is necessary to differentiate the right system to be used for the purpose.

It is possible to differentiate solid modeling environments according to their features. Every program has its own individual modeling methods that have to be understood within the realm of design and manufacturing needs. These modeling environments can be categorized as follows[19]:

Concept modelers and rendering programs

These include sketching programs, which are geometric modelers primarily used for conceptual design and conceptual modelers with a strong emphasis on

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[18] MITCHELL, W J. "Construction Complexity" in: *CAAD Futures*. Ed. Bob Martens & Andre Brown. Springer, 2005. In 'HOWARD, Rob. "CAD, Curved Surfaces and Building Quality" in: *ITcon* (Volume 11, p. 427-436). 2006.'

[19] SCHODEK, Daniel; BECHTHOLD, Martin; GRIGGS, Kimo; KAO, Kenneth Martin and STEINBERG, Marco. *Digital Design and Manufacturing: CAD/CAM Applications in Architecture and Design.* John Wiley & Sons, INC. 2005.

rendering. During conceptual design, initial shape generation is the most important element. These programs are usually used for visualization and representation purposes, and include programs such as Google SketchUP, McNeel Rhinoceros or Autodesk 3D Studio Max.

Animation programs

These were initially developed for entertainment industry. By using these programs, simulations, visualizations and dynamic animations can be created, which may also be useful on large and complex design projects. Programs such as Autodesk Maya or Softimage are in this group.

Entity-based drafting programs

Primarily facilitating the creation of 2D design documentation, these environments are universally useful as drafting tools. They rely on drawing entities like lines, polylines, arcs, splines, etc. to model shapes. Programs such as Autodesk AutoCAD or Nemetschek VectorWorks are in this group.

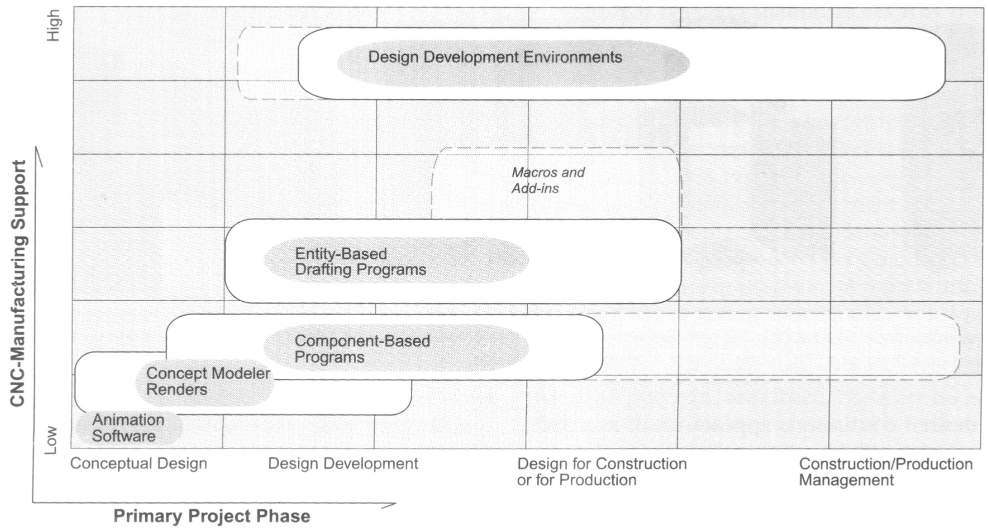
Component-based programs

These are specially developed for architectural design, and rely on 3D components or objects to represent major elements of design. Architectural Desktop, Autodesk Revit, MicroStation, Nemetschek Allplan or Graphisoft ArchiCAD are commonly used software.

Design development programs

These are used where an existing basic scheme is to be developed into a functional, aesthetically and technically resolved design. They are feature-based, dimensionally-driven programs and show the way a model is structured. The design models from these environments can serve in the generation of instructions for the programming of CNC machining. Such environments include Dassault Systems CATIA, SolidWorks, PTC Pro/ENGINEER or UniGraphics.

Table 3.2 Simplified mapping of geometric modelers.[20]



In Table 3.2 a comparison among the types of environments can be seen. From down to up the table shows how much the type of program supports CNC manufacturing and from left to right they are shown in their usage in the project design phases. It can be said that design development programs are the most supportive environments when CAD/CAM systems are concerned.

3.3.2 Future Expectations/Observations

Computational modeling is never something that should be started without an awareness of the medium. It does not design for the architect, and in no way will it ever take the place of the architect. It is both a result of the architect's mind and a process s/he uses to explore and design. The way of exploration should be thoroughly understood in order to be used in its best way. As it is essential to understand the potential of the materials used for physical models, here, in the

[20] Ibid.

computational world, the medium, being highly different from the media of physical modeling, has potentials of its own and changes the design consideration of the architect.

It is important to become familiar with the computational medium being used, as it can be easy to become lost in the complexity of the medium in between the numbers, nodes and NURBS. The entry of the fourth dimension – time – into the design process, the possibility of editing (being an editable tool), recording every change that is done throughout the process, being able to revise to any step taken before, each constitutes one of the new and important aspects of computational technologies proposed to the design process that architecture needs to reconsider.

This study aims to investigate the potentials of CAD/CAM technology regarding the architectural design process, from the initial design phase to the actual manufacturing processes. The case study analyzed in the following two chapters will attempt to illustrate a digital design process in this respect.

CHAPTER 4

CASE STUDY PART I: DESIGN CONSIDERATIONS

It has been explained in the previous chapter that modeling is an essential tool for the architect, and the evolving definition of the architectural model to collaborative design environment is a rather recent concept. In this study, it is aimed to illustrate the CAD/CAM process by providing an example, in which a design object is modeled by means of CAD and then manufactured using CAM.

It is necessary for the architect to have a foresight of the production phase of building; i.e. "the designer/architect needs to know how things work, how they are made and how materials behave and their qualities".[1] When using CAD/CAM, the collaboration between the components of the system is an essential need. The digital design environment and the modeling method become important as they affect the production.

Thus, design considerations for CAD/CAM and the different approaches of different modeling environments are investigated. Comparisons between modeling methods and the various outcomes, together with their affects on the production process, are examined within the case study.

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[1] THORNTON, John. "Fabrication Research" in: *Architectural Design* (Volume 75, Issue 4, p. 100-103). July/August, 2005. (p.101)

4.1 Preliminary Design

The case study intends to give a general perspective of CAD/CAM, focused on the differences between modeling environments and their possible outcomes for the manufacturing needs. The ***torus,*** a complex object having a multi-axis definition of variables, has been chosen to illustrate the process. In the definition of topology in mathematics, the torus is also an important shape as it has a single continuous surface and a hole, and is commonly used to illustrate digital modeling techniques in CAD.

The geometrical definition of a torus can be simplified as being a surface of revolution. It is generated by revolving a circle in 3D space about an axis coplanar with the circle. The torus is made of two main variables: The first variable is set to give the radius of the torus, i.e. the circle, centered on the center of the torus, and having its perimeter through the centers of the tube section. The second variable is the tube section, which is the revolving circle having its center on the perimeter of the circle defining the torus radius. The planes of these two variables have to be perpendicular to each other, meaning that if the first variable is lying on the 'xy' plane, then the second variable has to be perpendicular to this plane (sweeping around the 'z' axis).

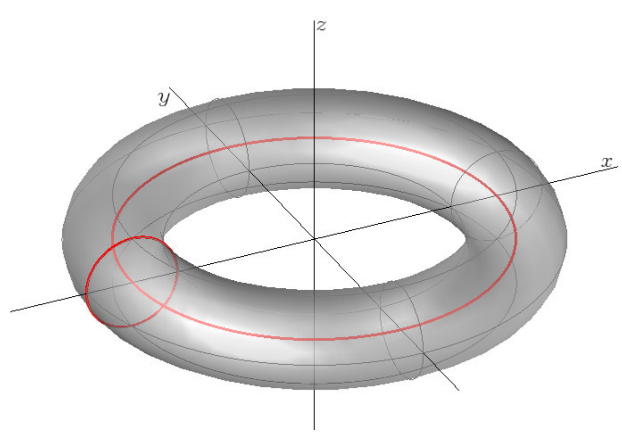


Figure 4.1 The torus

The surface of the torus body is defined in 3D space and is continuous and smooth, without any discontinuity or fold. During modeling, a torus object can be created having a smooth surface definition or with segments on the face body according to the allowances of the software and/or the commands used. Not only the model, but also the manufacturing process for the torus has a complexity of its own. Various ways can be found for producing the torus. Here it should be pointed out that design construction methods differ according to the allowances of the CNC.

It is possible to create the torus in various ways using different software, and some software includes previously-defined torus objects in their solids libraries. In this study the torus has been modeled in different CAD applications. Different construction methods are examined. The major dimensions of the torus are kept the same in every model to prevent any bias arising from dimensional inconsistencies. The dimensions of the torus are chosen as:

The radius of the torus = 120 units

The radius of the tube section = 30 units

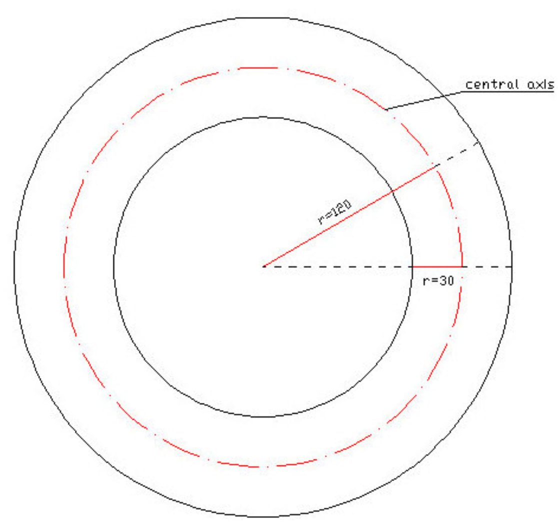


Figure 4.2 Dimensions for the torus object

4.2 Computational Modeling

For the modeling of the torus object several modeling environments have been chosen among the software applications that are generally used in architectural offices, by architects/students of architecture and/or by designers. Here, it must be explained that there has been no specific rule or given priority to any of the software chosen. It is not intended to make a comparison among the software in terms of one being better or the other worse, the aim rather being to understand what can or cannot be done with each of the software. Neither it is claimed that the explained modeling methods and commands for each type of application are the only possible methods, as these are only selected cases for the modeling of a torus.

During the study it has been observed that different versions of the same software can vary in terms of the modeling methods. The problems encountered in earlier versions are usually resolved (changed and/or developed) in the later versions. In this study, it is not intended to investigate the applications, their versions and their ways of modeling, but rather to establish the way of structuring in the geometrical/numerical setting of the model, as for the manufacturing process the numerical definition of the object has to be precise.

4.2.1 Entity-Based Drafting Programs

Entity-based drafting programs are usually used for the preparation of 2D design documentation, although they generally allow the creation of 3D objects. For the present case study, AutoCAD, the most widely used entity-based software in architectural offices, has been chosen.

AutoCAD software creates objects in DWG (drawing) format which is used for storing two or three dimensional design data or metadata. Being native to Autodesk packages, DWG format is also supported by many other applications[2].

As is common for most applications, there are solid libraries in the programs for the drawing/modeling of frequently used shapes, such as box, sphere, cylinder, cone, pyramid, etc. The torus is an object included in the libraries of many modeling software other than AutoCAD. In such software it is necessary to declare at least three variables, namely the location coordinates/point, the radius/diameter of the torus, and the radius/diameter of the tube section, in order to be able to draw a torus. How these variables are declared may vary in different applications.

In AutoCAD software, after choosing the specific location of the command, the user is first asked to specify the center point of the torus for the location of the object. Then the radii of the torus and the tube section are given respectively and the software creates the torus according to the definitions/proportions specified by the user. The torus defined in the solid library of AutoCAD software can be seen in Figure 4.3. The properties of such a torus can be followed in Table 4.1.

Another method used in modeling a torus in entity-based programs is by using the variations of ‘extrude’ commands. These commands differ in the way the model is obtained, but the algorithm behind, and thus, the properties of the modeled object are usually the same. The extrude command is usually used to give thickness to 2D entities, but in cases like modeling a torus, a path can be associated for the extrusion. This type of extrusion is referred to as ‘sweep’, being an additional command.

[2] http://en.wikipedia.org/wiki/DWG (December 2007)

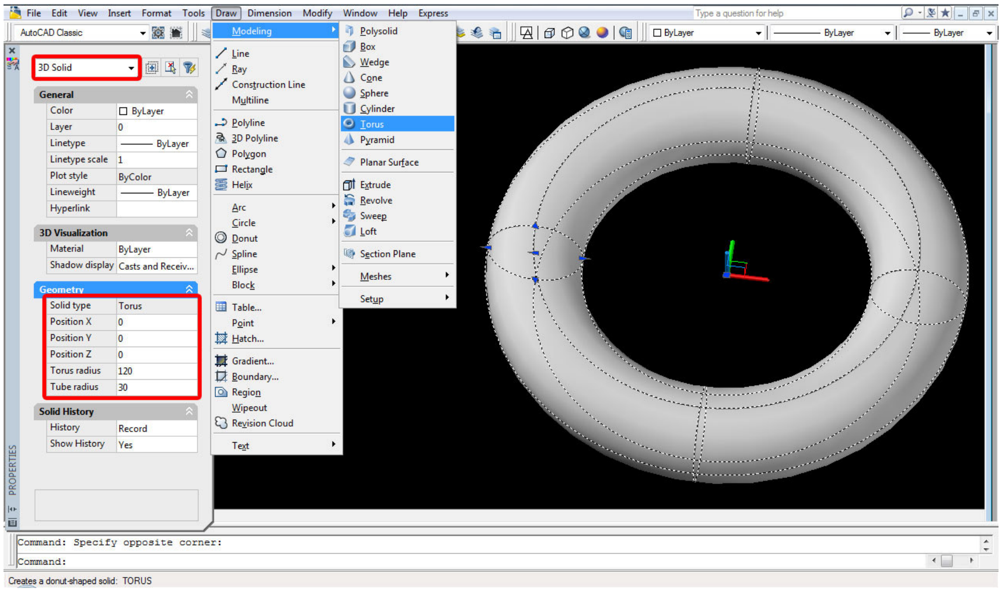
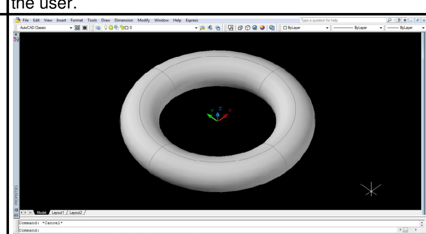


Figure 4.3 The torus modeled from the solids library of AutoCAD software.

Table 4.1 Properties of the torus modeled from the solids library of AutoCAD software.

<table>
<tr><td colspan="2"></td><td colspan="5">AutoCAD (.dwg)</td></tr>
<tr><td rowspan="8">VOLUME</td><td>COMMANDS</td><td colspan="5">Solids Library (draw/solids/torus or draw/modeling/torus)</td></tr>
<tr><td>HOW TO MODEL</td><td colspan="5">After choosing the specific location of the command, the user is firstly asked to specify the center point of the torus for the location of the object. Later, the radiuses of the torus and the tube section are given respectively and the software creates the torus according to the definitions specified by the user.</td></tr>
<tr><td>MODEL PROPERTY</td><td colspan="2"></td><td colspan="3"><table>
<tr><td colspan="3">PROPERTIES</td></tr>
<tr><td>File Format</td><td colspan="2">.dwg</td></tr>
<tr><td>Object Type</td><td colspan="2">3D solid (polygon)</td></tr>
<tr><td rowspan="3">Units</td><td>torus radius</td><td>120</td></tr>
<tr><td>tube radius</td><td>30</td></tr>
<tr><td>isoline</td><td>4</td></tr>
<tr><td colspan="3">Modeling Time</td></tr>
<tr><td colspan="3">counted in seconds</td></tr>
<tr><td colspan="3">Modeling Cost</td></tr>
<tr><td colspan="3">software cost</td></tr>
</table></td></tr>
<tr><td rowspan="3">DATA EXCHANGE</td><td>*.sat, *.stl, *.dxf</td><td colspan="4">Data exchange is needed, and the object is transformed from a *.dwg file into another file format from the export property of the software.</td></tr>
<tr><td>Precision</td><td colspan="4">The object does not lose its property.</td></tr>
<tr><td>Cost</td><td colspan="4">NA</td></tr>
<tr><td>MANUFACTURING</td><td>-</td><td colspan="4">The object can be converted into a manufacturable file format, but as long as these cannot be opened by target applications the file cannot be used.</td></tr>
</table>

To model a torus using the extrude command the user must first specify two circles. The first one is to define the radius of the torus object and the second to define the radius of the tube section. These are to be perpendicular to each other so that the tube section's center will lie on the first circle (Figure 4.4). The circle for the tube section will then be extruded along the path (circle defining the torus object). The torus modeled by the extrude command of AutoCAD software can be seen in Figure 4.5 and the properties of the torus in Table 4.2.

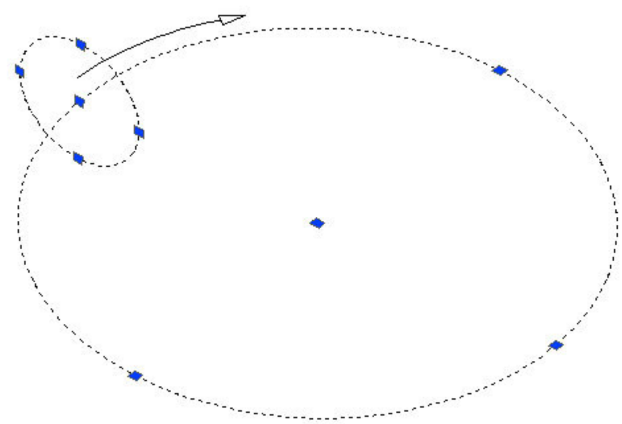


Figure 4.4 Location of circles for extrusion commands.

The 'revolve' command can also be used to model a torus. Revolve simply means rotating an object around a central point. To obtain a torus using the revolve command, it is necessary to revolve a circle (being the diameter of the tube) around an axis. The definition of the axis can vary among applications. It can be given as a line object perpendicular to the center point of the torus. The revolution axis can also be given as a specific point according to the global axes of the drawing and the location of the circle. The torus model obtained using the revolve command will be the same in definition with the torus obtained using the extrude command. The torus modeled with the revolve command of AutoCAD software can be seen in Figure 4.6, and the properties of the torus in Table 4.3.

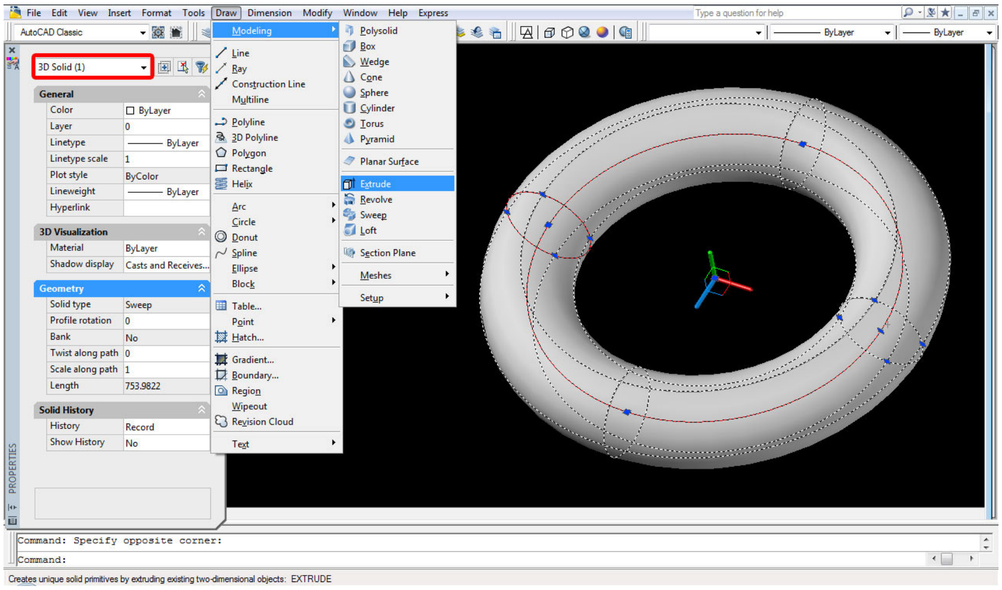
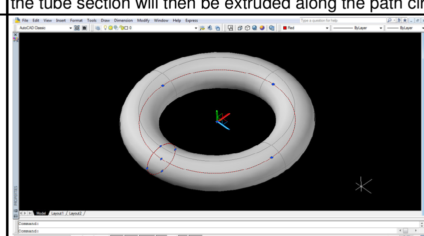


Figure 4.5 The torus modeled using the extrude command of AutoCAD software.

Table 4.2 Properties of the torus modeled using the extrude command of AutoCAD software.

<table>
<tr><td colspan="2"></td><td colspan="4">AutoCAD (.dwg)</td></tr>
<tr><td rowspan="7">VOLUME</td><td>COMMANDS</td><td colspan="4">Extrude commands (extrude and sweep)</td></tr>
<tr><td>HOW TO MODEL</td><td colspan="4">The user has to specify two circles to model a torus with the extrude command . First one is to define the radius of the torus object, and the other is to define the tube section. These are perpendicular to each other; so that the tube section's center will lie on the first circle. The circle for the tube section will then be extruded along the path circle.</td></tr>
<tr><td>MODEL PROPERTY</td><td colspan="2"></td><td colspan="2">PROPERTIES
File Format | .dwg
Object Type | 3D solid (polygon)
Units | torus radius | 120
tube radius | 30
isoline | 4
Modeling Time
counted in seconds
Modeling Cost
software cost</td></tr>
<tr><td rowspan="3">DATA EXCHANGE</td><td>*.sat, *.stl, *.dxf</td><td colspan="3">Data exchange is needed, and the object is transformed from a *.dwg file into another file format from the export property of the software.</td></tr>
<tr><td>Precision</td><td colspan="3">The object does not lose its property.</td></tr>
<tr><td>Cost</td><td colspan="3">NA</td></tr>
<tr><td>MANUFACTURING</td><td>-</td><td colspan="3">The object can be converted into a manufacturable file format, but as long as these cannot be opened by target applications the file cannot be used.</td></tr>
</table>

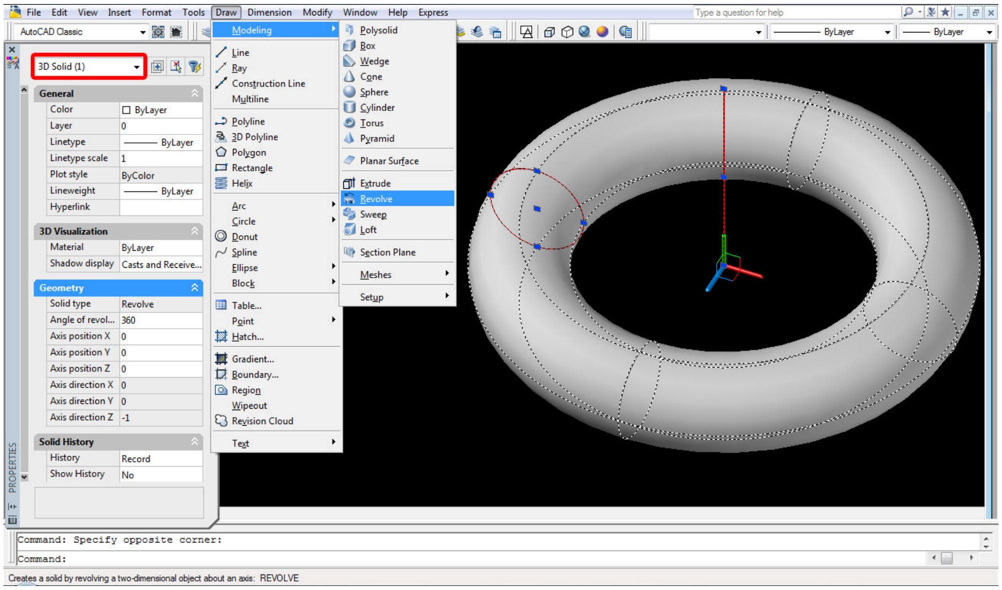
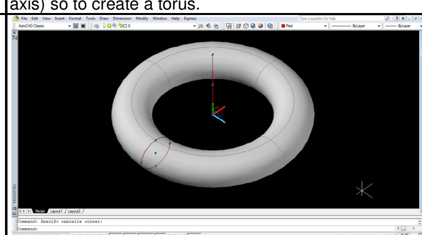


Figure 4.6 The torus modeled using the revolve command of AutoCAD software.

Table 4.3 Properties of the torus modeled using the revolve command of AutoCAD software.

		AutoCAD (.dwg)	
VOLUME	COMMANDS	Revolve command	
	HOW TO MODEL	To model a torus by using the revolve command, a circle for the tube section and a line perpendicular to the center of the torus object are drawn. The circle is revolved around the line (the axis) so to create a torus.	
	MODEL PROPERTY		PROPERTIES File Format: .dwg Object Type: 3D solid (polygon) Units: torus radius 120; tube radius 30; isoline 4 Modeling Time: counted in seconds Modeling Cost: software cost
	DATA EXCHANGE	*.sat, *.stl, *.dxf	Data exchange is needed, and the object is transformed from a *.dwg file into another file format from the export property of the software.
		Precision	The object does not lose its property.
		Cost	NA
	MANUFACTURING	-	The object can be converted into a manufacturable file format, but as long as these cannot be opened by target applications the file cannot be used.

The 'loft' command, being another useful command in modeling environments, can also be used to model a torus. Loft is used to fill between two or more objects with a solid or a surface model. The fill is usually done according to the locations of the objects in relation to each other. For example, when two straight lines lying on the same plane are lofted, the end result is a plane. Two objects are connected with a planar surface with a one-to-one correspondence with the minimum distance between connected points. However, it is also possible to define a path of correspondence. In the example of modeling a torus with the loft command, it is necessary to define at least two circles of the tube section, which are then lofted along a path. The path is the circle defining the torus shape, similar to the one that had been used for the extrude command.

In AutoCAD software, the loft command has a different algorithm than the extrusion commands i.e. extrude, sweep and revolve; thus, the lofted torus has a different definition of its shape than the previously modeled tori. Again being a 3D solid the lofted torus is defined with more points in space. The torus obtained from the loft command of AutoCAD software can be seen in Figure 4.7 and its properties in Table 4.4.

The tori that have been obtained thus far were solid objects, but it is also possible to model surface tori. The basic definitions of the previously described commands are to obtain volumes when applied on closed 2D entities. However, it is possible to model closed surface meshes. Usually in modeling environments, the names of the commands are changed so as to differentiate the modeled objects; i.e. they are surfaces or volumes. In AutoCAD software this differentiation is made by the 'revolved mesh' command which works similar to the revolve command but creates polygon meshes.

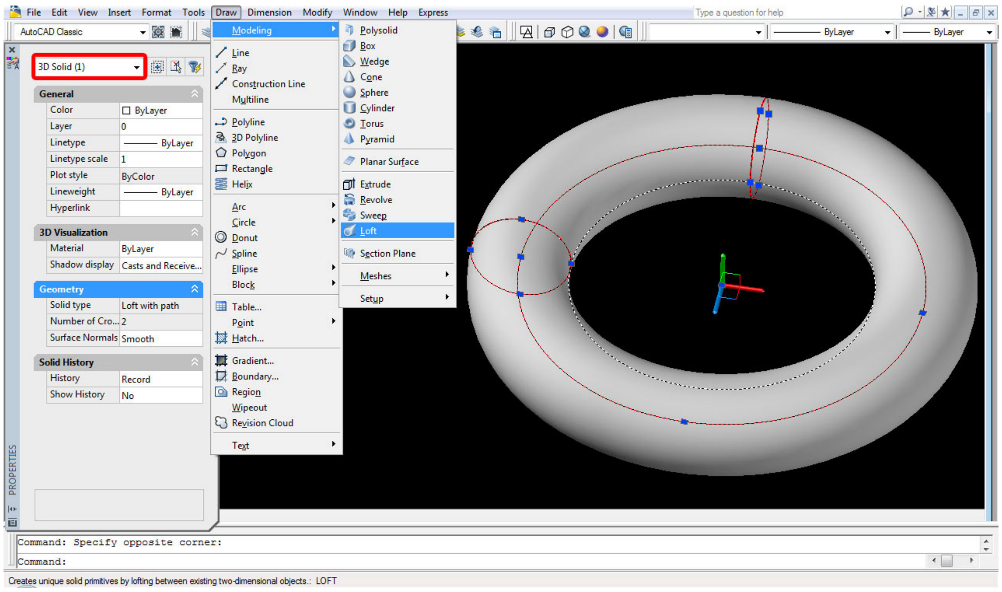
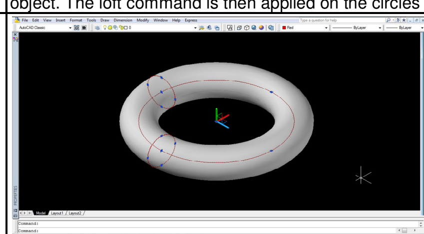


Figure 4.7 The torus modeled using the loft command of AutoCAD software.

Table 4.4 Properties of the torus modeled using the loft command of AutoCAD software.

<table>
<tr><td colspan="2"></td><td colspan="2">AutoCAD (.dwg)</td></tr>
<tr><td rowspan="7">VOLUME</td><td>COMMANDS</td><td colspan="2">Loft command</td></tr>
<tr><td>HOW TO MODEL</td><td colspan="2">The user draws at least two circles (for the tube section) lying on the circle (the path) of the torus object. The loft command is then applied on the circles along the path.</td></tr>
<tr><td>MODEL PROPERTY</td><td colspan="2"><table><tr><td colspan="3">PROPERTIES</td></tr><tr><td>File Format</td><td colspan="2">.dwg</td></tr><tr><td>Object Type</td><td colspan="2">3D solid (polygon)</td></tr><tr><td rowspan="3">Units</td><td>torus radius</td><td>120</td></tr><tr><td>tube radius</td><td>30</td></tr><tr><td></td><td></td></tr><tr><td colspan="3">Modeling Time</td></tr><tr><td colspan="3">counted in seconds</td></tr><tr><td colspan="3">Modeling Cost</td></tr><tr><td colspan="3">software cost</td></tr></table></td></tr>
<tr><td rowspan="3">DATA EXCHANGE</td><td>*.sat, *.stl, *.dxf</td><td>Data exchange is needed and the object is transformed from a *.dwg file into another file format from the export property of the software.</td></tr>
<tr><td>Precision</td><td>The object does not lose its property and the definition is longer.</td></tr>
<tr><td>Cost</td><td>NA</td></tr>
<tr><td>MANUFACTURING</td><td>-</td><td>The object can be converted into a manufacturable file format, but as long as these cannot be opened by target applications the file cannot be used.</td></tr>
</table>

Polygon meshes that define curves in space are like segmented lines; the more lines/segments used means the more precise and realistic that the model will appear. The number of divisions of the polygon mesh can be defined. For example, in AutoCAD software, these divisions are known as 'surface tabs values', which the user must define before using the mesh modeling commands.

The difference that these surface tab values (mesh divisions) make can clearly be seen when the values are chosen as small as three or four. If one tries to model a torus using the revolved mesh command choosing the surface tab values as three, a triangular torus will be obtained. Likewise, if the value of four has been chosen for the surface tab values, a rectangular torus is modeled. These tori can be seen in Figure 4.8.

Thus the values of the division numbers have to be increased so that at least a ***visually smooth circular*** torus can be created. The polygon mesh torus obtained from the revolved mesh command of AutoCAD software with surface tab values 30 can be seen in Figure 4.9. The properties of the torus are given in Table 4.5.

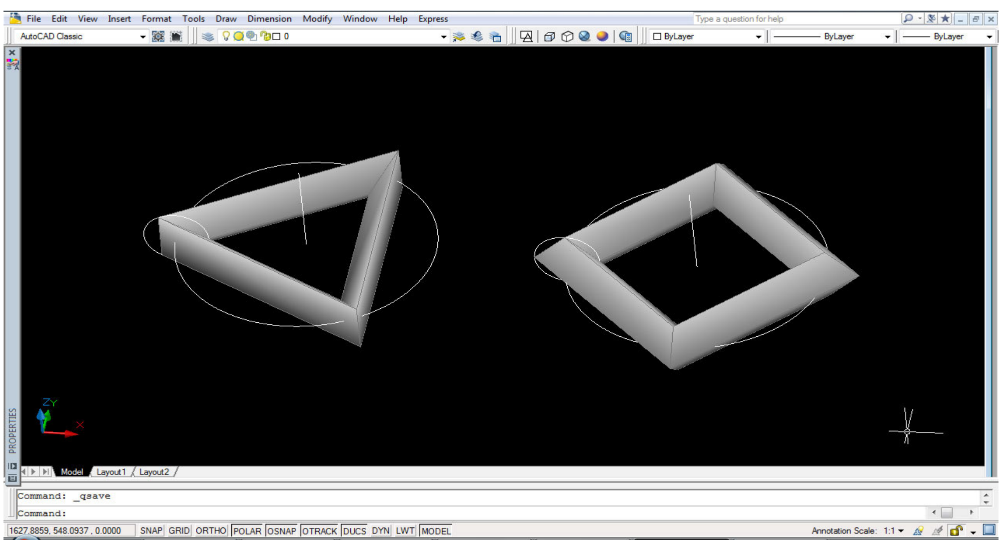


Figure 4.8 Polygon tori modeled using the revolved mesh command of AutoCAD software with surface tab values three and four respectively.

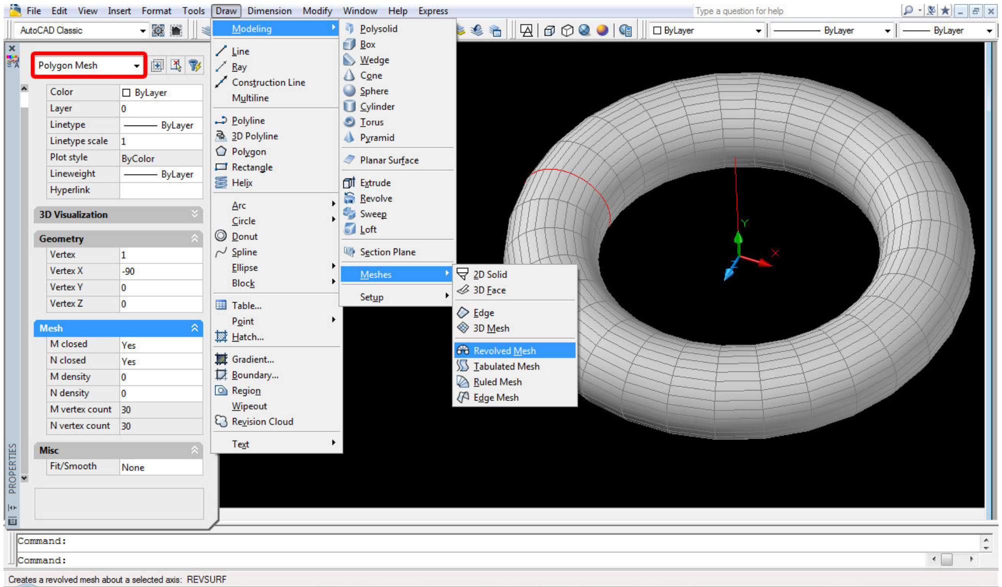
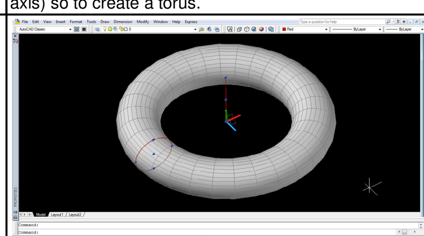


Figure 4.9 The polygon mesh torus modeled using the revolved mesh command of AutoCAD software with surface tab values 30.

Table 4.5 Properties of the polygon mesh torus modeled using the revolved mesh command of AutoCAD software with surface tab values 30.

		AutoCAD (.dwg)			
SURFACE	COMMANDS	Revolved mesh command			
	HOW TO MODEL	To model a torus by using the revolved mesh command, one circle for the tube section and a line perpendicular to the center of the torus object are drawn. The circle is revolved around the line (the axis) so to create a torus.			
	MODEL PROPERTY		PROPERTIES		
			File Format	.dwg	
			Object Type	Polygon Mesh	
			Units	torus radius	120
				tube radius	30
				vertex count	30
			Modeling Time		
			counted in seconds		
			Modeling Cost		
			software cost		
	DATA EXCHANGE	*.dxf	Data exchange is needed but the object cannot be transformed from a *.dwg file into another file format as long as it is a surface mesh. The object can be saved as *.dxf format but it cannot be used.		
		Precision	NA		
		Cost	NA		
	MANUFACTURING	-	The object cannot be converted into a manufacturable file format.		

4.2.2 Concept Modelers, Rendering and Animation Programs

Concept modelers, rendering and animation programs are mostly used for representation and visualization purposes during conceptual design. They have high quality render options, calculating light/shadow effects together with perspective and camera options. Photo-realistic images and animations can be obtained from these programs. Within a variety of modeling options, it is both possible to model 3D shapes from 2D entities, and to modify previously defined 3D shapes on their edges, nodes and faces so as to model topologically-similar 3D shapes.

For the purpose of this study, 3ds Max software has been chosen, which can be said to be the most widely used rendering program in architectural offices. 3ds Max is a modeling and rendering environment that is used mostly for the creation of photo-realistic images of works of architectural design. The software creates files in the MAX file format having a variety of import-export options to other file formats.

As was the case in entity-based modeling programs, rendering programs also allow the modeling of tori in several ways, mostly similar to the ways described above. Objects in the library of 3ds Max software, known as standard primitives, include the torus together with a variety of other 3D shapes. This torus is a polygon mesh and it can be seen in Figure 4.10 and Table 4.6.

Rendering programs have a variety of visualization options; i.e. the same model having the same geometrical/numerical definition can be ***viewed*** differently. In the example of the torus object in 3ds Max software, the torus from the standard primitives is a polygon mesh that actually has a segmented surface. The smoothness of the object can be set from the modify panel of 3ds Max software, in which the parameters related with the model can be edited. The same torus can be observed in Figure 4.11 with the two different options of being smooth or not.

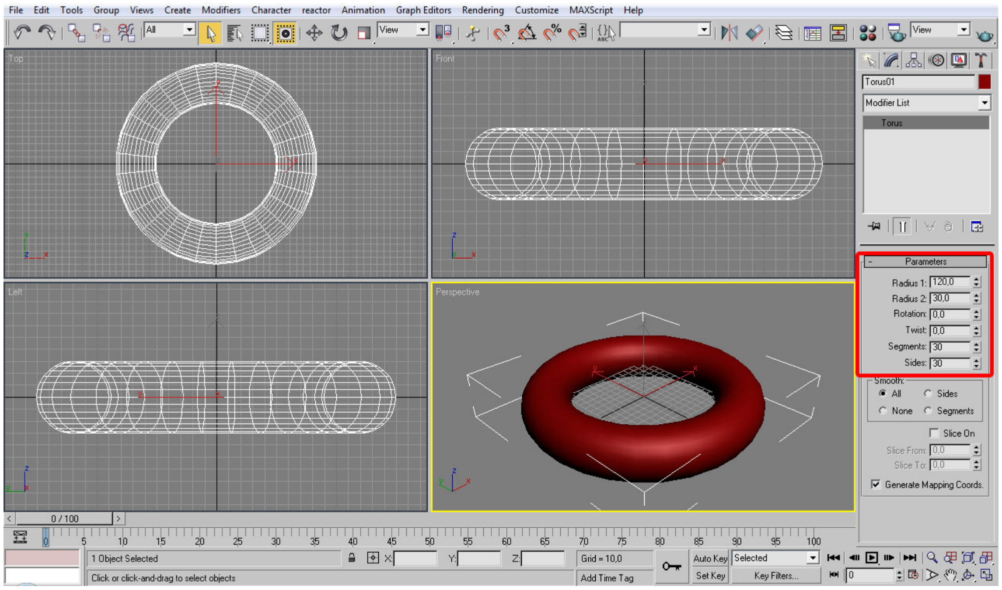
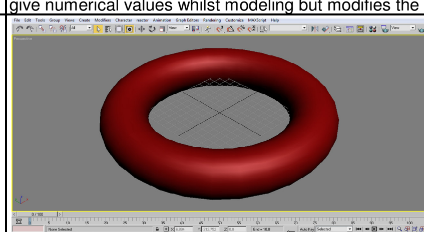


Figure 4.10 The torus modeled from the standard primitives library of 3ds Max software.

Table 4.6 Properties of the torus modeled from the standard primitives library of 3ds Max software

<table>
<tr><td colspan="2"></td><td colspan="2">3ds MAX (.max)</td></tr>
<tr><td rowspan="7">SURFACE</td><td>COMMANDS</td><td colspan="2">Solids Library (create/standard primitives/torus)</td></tr>
<tr><td>HOW TO MODEL</td><td colspan="2">Modelin a torus is a three stepped process in which the user clicks three different points, one for the placement of the object and the other two for the two radiuses of the torus. The user does not give numerical values whilst modeling but modifies the object afterwards.</td></tr>
<tr><td>MODEL PROPERTY</td><td colspan="2">
<table>
<tr><td colspan="3">PROPERTIES</td></tr>
<tr><td>File Format</td><td colspan="2">.max</td></tr>
<tr><td>Object Type</td><td colspan="2">Polygon Mesh</td></tr>
<tr><td rowspan="3">Units</td><td>torus radius</td><td>120</td></tr>
<tr><td>tube radius</td><td>30</td></tr>
<tr><td>segments</td><td>30</td></tr>
<tr><td colspan="3">Modeling Time</td></tr>
<tr><td colspan="3">counted in seconds</td></tr>
<tr><td colspan="3">Modeling Cost</td></tr>
<tr><td colspan="3">software cost</td></tr>
</table></td></tr>
<tr><td rowspan="3">DATA EXCHANGE</td><td>*.3ds, *.dxf</td><td>Data exchange is needed, and the object can be transformed from a *.max file into another file format from the export property of the software.</td></tr>
<tr><td>Precision</td><td>The object does not lose its property but is not a smooth torus.</td></tr>
<tr><td>Cost</td><td>NA</td></tr>
<tr><td>MANUFACTURING</td><td>-</td><td>The object can be converted into a manufacturable file format, but as long as these cannot be opened by target applications the file cannot be used.</td></tr>
</table>

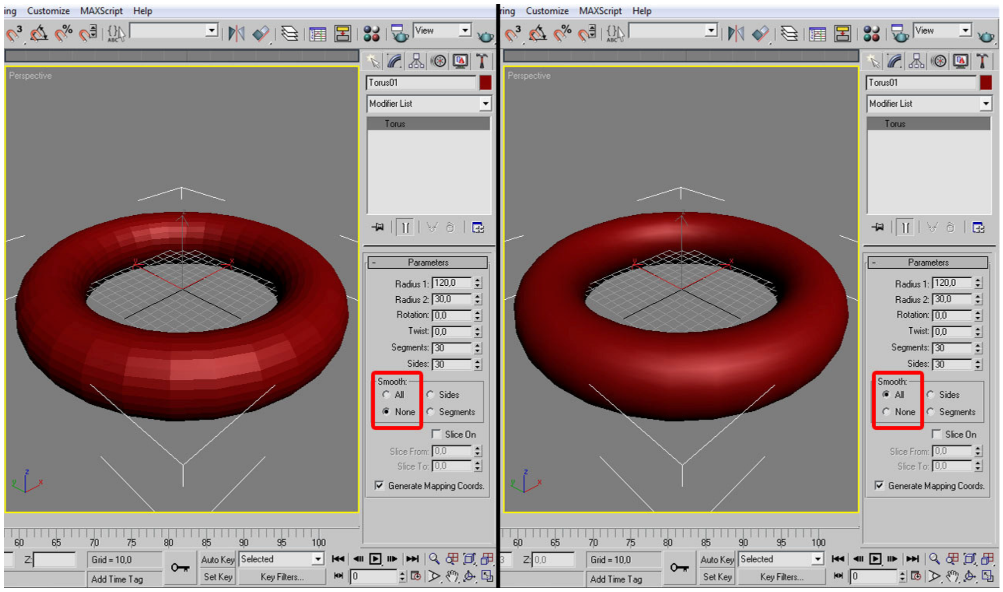


Figure 4.11 Smoothing option of the 3ds Max software. Being the same torus, the smoothing option has a visual effect on the object.

A torus shape can also be modeled in rendering programs by using the basic commands and obtaining the model from 2D entities. Although having similar properties that have been described in the previous section, the names of the commands can vary in different applications.

In 3ds Max, the loft and lathe commands can be used to model tori. The working principle of the loft command in 3ds Max is similar to the sweep (extrude path) command previously described. The circle defining the tube section is extruded (here, lofted) along a circular path defining the torus diameter (Figure 4.12 and Table 4.7). On the other hand, the lathe command operates in a similar way to the revolve command (Figure 4.13 and Table 4.8).

The objects created using these methods in 3ds Max are also polygon meshes that can again be visually smoothened. However, the software can also change the type of the object; i.e. objects can be converted to NURBS or patch surfaces with the properties of the objects changing accordingly.

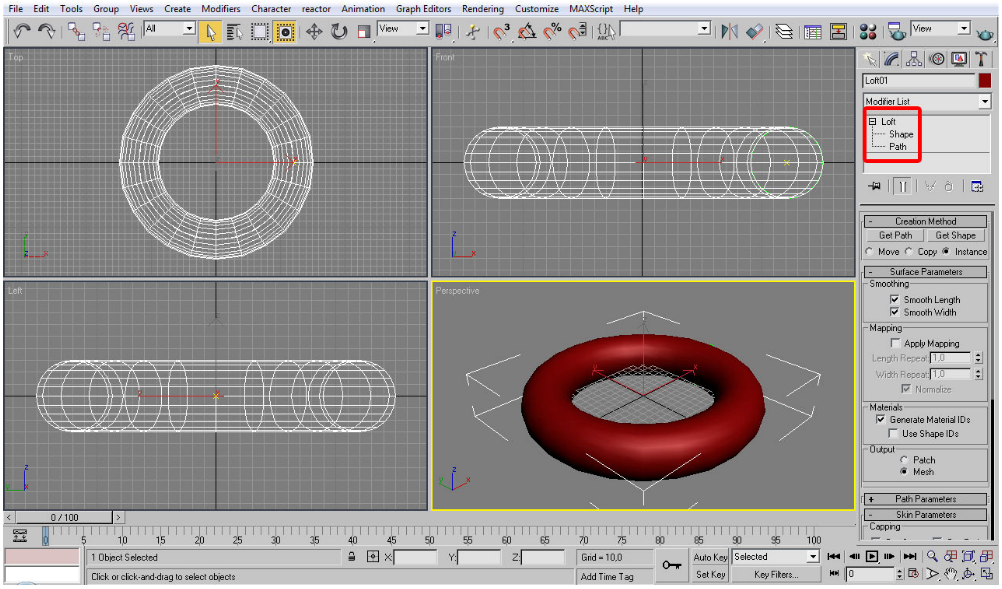
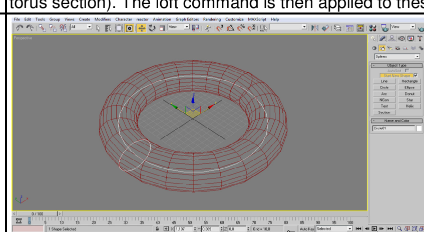


Figure 4.12 The torus modeled using the loft command of 3ds Max software.

Table 4.7 Properties of the torus modeled using the loft command of 3ds Max software.

		3ds MAX (.max)	
SURFACE	COMMANDS	Loft command	
	HOW TO MODEL	The user draws two circles; one is for the path (the torus diameter) and the next for the shape (the torus section). The loft command is then applied to these circles so that the torus is created.	
	MODEL PROPERTY		PROPERTIES File Format: .max Object Type: Polygon Mesh Units: torus radius 120; tube radius 30; segments 30 Modeling Time: counted in seconds Modeling Cost: software cost
	DATA EXCHANGE	*.3ds, *.dxf	Data exchange is needed and the object can be transformed from a *.max file into another file format from the export property of the software.
		Precision	The object does not lose its property but is not a smooth torus.
		Cost	NA
	MANUFACTURING	-	The object can be converted into a manufacturable file format, but as long as these cannot be opened by target applications the file cannot be used.

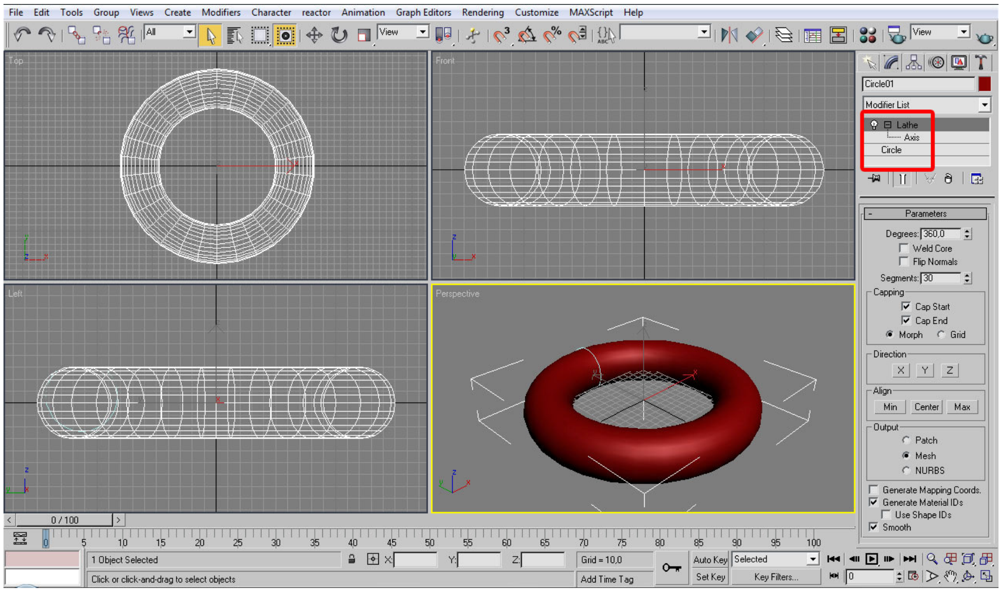
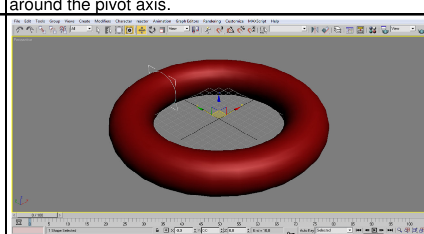


Figure 4.13 The torus modeled using the lathe command of 3ds Max software.

Table 4.8 Properties of the torus modeled using the lathe command of 3ds Max software.

<table>
<tr><td colspan="2"></td><td colspan="5">3ds MAX (.max)</td></tr>
<tr><td rowspan="7">SURFACE</td><td>COMMANDS</td><td colspan="5">Lathe command</td></tr>
<tr><td>HOW TO MODEL</td><td colspan="5">Lathe command works like the revolve command, but here instead of drawing an axis the pivot of the first circle is moved to the required revolving location (being the center of the torus) and lathed around the pivot axis.</td></tr>
<tr><td>MODEL PROPERTY</td><td colspan="2"></td><td colspan="3"><table>
<tr><td colspan="3">PROPERTIES</td></tr>
<tr><td>File Format</td><td colspan="2">.max</td></tr>
<tr><td>Object Type</td><td colspan="2">Polygon Mesh</td></tr>
<tr><td rowspan="3">Units</td><td>torus radius</td><td>120</td></tr>
<tr><td>tube radius</td><td>30</td></tr>
<tr><td>segments</td><td>30</td></tr>
<tr><td colspan="3">Modeling Time</td></tr>
<tr><td colspan="3">counted in seconds</td></tr>
<tr><td colspan="3">Modeling Cost</td></tr>
<tr><td colspan="3">software cost</td></tr>
</table></td></tr>
<tr><td rowspan="3">DATA EXCHANGE</td><td>*.3ds, *.dxf</td><td colspan="4">Data exchange is needed and the object can be transformed from a *.max file into another file format from the export property of the software.</td></tr>
<tr><td>Precision</td><td colspan="4">The object does not lose its property but is not a smooth torus.</td></tr>
<tr><td>Cost</td><td colspan="4">NA</td></tr>
<tr><td>MANUFACTURING</td><td>-</td><td colspan="4">The object can be converted into a manufacturable file format, but as long as these cannot be opened by target applications the file cannot be used.</td></tr>
</table>

There exist a wide range of rendering and animation programs. Among these 3ds Max software has been widely accepted by architects as the most suitable visualization and representation medium, not only because the software can create photo-realities better than many other software in the field but also because of its wide range of import-export options. There are other examples of rendering and animation environments in use by architects that do not support other file formats, of which Maya software, a highly progressed modeling and animation environment, is one. Maya software is used both by architects, designers and animators, and creates files in the MB format. As the format does not support and is not supported by other file formats, creating data for manufacturing and/or analysis can be problematic. However, for the designer the software offers a wide range of possibilities for modeling and form generation.

To model a torus in Maya software, the program has several options. The object library includes both polygonal and surface objects. Thus, there are two tori in the library; one is the polygon torus and the other the surface torus. As their names suggest, the polygon torus is a polygon object and the surface torus is a NURBS object. These can be seen in Figure 4.14 and 4.15 respectively.

In Maya it is also possible to model objects whilst modifying 2D objects to obtain 3D objects. The ‘revolve’ command can be used here, so by revolving a circle around an axis a torus object can be modeled. Here, peculiar to this software, the revolve command has an options screen in which the revolving axis and dimensions are chosen for the required proportions. The revolved surface torus modeled using Maya software can be seen in Figure 4.16. The properties of each model can be followed from the tables (Table 4.9, 4.10 and 4.11) following the figures.

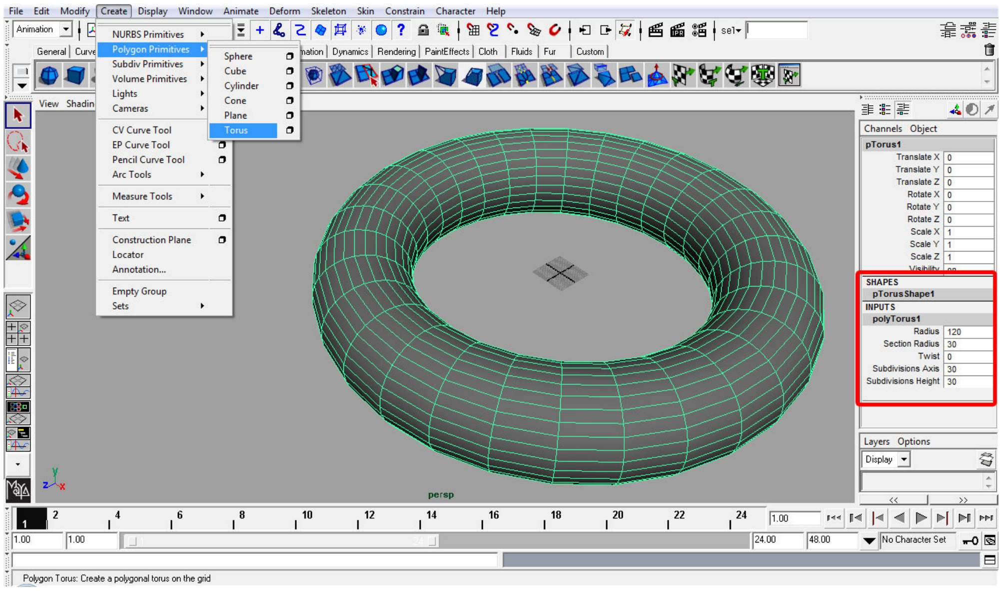
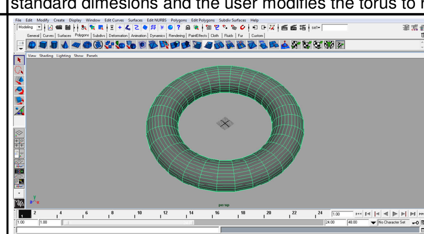


Figure 4.14 The torus modeled from the polygon primitives library of Maya software.

Table 4.9 Properties of the torus modeled from the polygon primitives library of Maya software.

		Maya (.mb)			
VOLUME	COMMANDS	Polygon Torus (create/polygon primitives/torus)			
	HOW TO MODEL	While choosing the specific location of the command, the application creates a polygon torus with standard dimesions and the user modifies the torus to required dimesions from the channel box.			
	MODEL PROPERTY		PROPERTIES		
			File Format	.mb	
			Object Type	Polygon	
			Units	torus radius	120
				tube radius	30
				segments	30
			Modeling Time	counted in seconds	
			Modeling Cost	software cost	
	DATA EXCHANGE	-	Data exchange cannot be done as long as the export option of the application does not have options.		
		Precision	NA		
		Cost	NA		
	MANUFACTURING	-	The object cannot be converted into a manufacturable file format.		

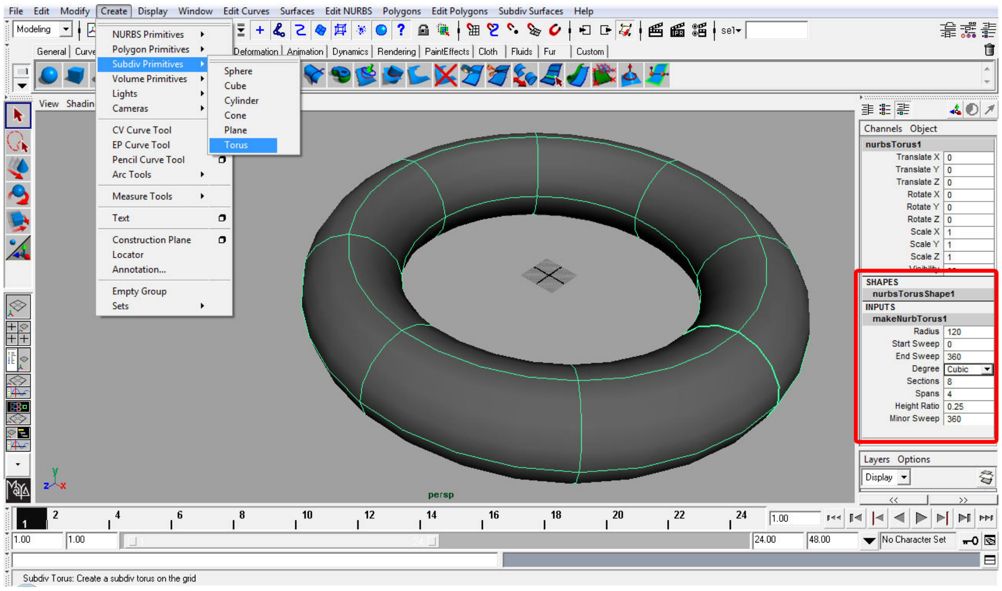
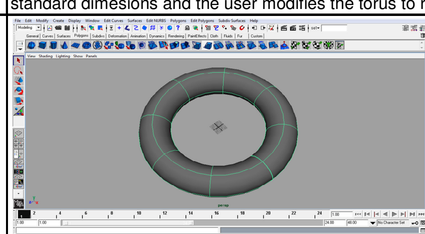


Figure 4.15 The torus modeled from the surface primitives library of Maya software.

Table 4.10 Properties of the torus modeled from the surface primitives library of Maya software.

<table>
<tr><td colspan="2"></td><td colspan="4">Maya (.mb)</td></tr>
<tr><td rowspan="8">SURFACE</td><td>COMMANDS</td><td colspan="4">NURBS Torus (create/subdivision primitives/torus)</td></tr>
<tr><td>HOW TO MODEL</td><td colspan="4">While choosing the specific location of the command, the application creates a NURBS torus with standard dimensions and the user modifies the torus to required dimensions from the channel box.</td></tr>
<tr><td>MODEL PROPERTY</td><td colspan="2"></td><td colspan="2"><table>
<tr><td colspan="3">PROPERTIES</td></tr>
<tr><td>File Format</td><td colspan="2">.mb</td></tr>
<tr><td>Object Type</td><td colspan="2">NURBS object</td></tr>
<tr><td rowspan="3">Units</td><td>torus radius</td><td>120</td></tr>
<tr><td>tube radius</td><td>30</td></tr>
<tr><td>sections</td><td>8</td></tr>
<tr><td colspan="3">Modeling Time</td></tr>
<tr><td colspan="3">counted in seconds</td></tr>
<tr><td colspan="3">Modeling Cost</td></tr>
<tr><td colspan="3">software cost</td></tr>
</table></td></tr>
<tr><td rowspan="3">DATA EXCHANGE</td><td>-</td><td colspan="3">Data exchange cannot be done as long as the export option of the application does not have options.</td></tr>
<tr><td>Precision</td><td colspan="3">NA</td></tr>
<tr><td>Cost</td><td colspan="3">NA</td></tr>
<tr><td>MANUFACTURING</td><td>-</td><td colspan="3">The object cannot be converted into a manufacturable file format.</td></tr>
</table>

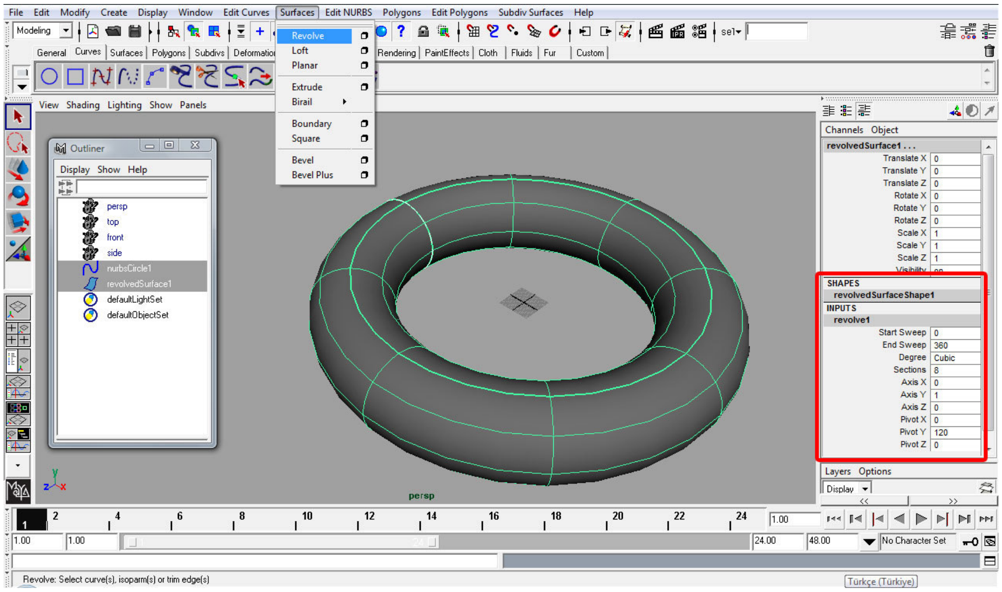
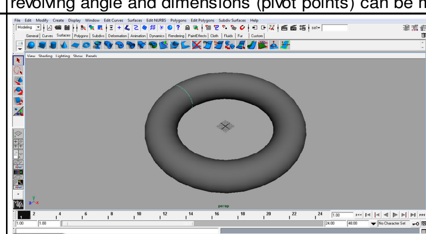


Figure 4.16 The torus modeled using the revolve command of Maya software.

Table 4.11 Properties of the torus modeled using the revolve command of Maya software.

<table>
<tr><td colspan="2"></td><td colspan="5">Maya (.mb)</td></tr>
<tr><td rowspan="6">SURFACE</td><td>COMMANDS</td><td colspan="5">Revolve command</td></tr>
<tr><td>HOW TO MODEL</td><td colspan="5">A circle defining the tube section is revolved around a previously defined revolve axis so to create the torus. The revolve command has an options screen in which the revolving axis, revolving angle and dimensions (pivot points) can be modified prior to modeling.</td></tr>
<tr><td>MODEL PROPERTY</td><td colspan="2"></td><td colspan="3">
<table>
<tr><td colspan="3">PROPERTIES</td></tr>
<tr><td>File Format</td><td colspan="2">.mb</td></tr>
<tr><td>Object Type</td><td colspan="2">NURBS object</td></tr>
<tr><td rowspan="3">Units</td><td>torus radius</td><td>120</td></tr>
<tr><td>tube radius</td><td>30</td></tr>
<tr><td>sections</td><td>8</td></tr>
<tr><td colspan="3">Modeling Time</td></tr>
<tr><td colspan="3">counted in seconds</td></tr>
<tr><td colspan="3">Modeling Cost</td></tr>
<tr><td colspan="3">software cost</td></tr>
</table>
</td></tr>
<tr><td rowspan="3">DATA EXCHANGE</td><td>-</td><td colspan="4">Data exchange cannot be done as long as the export option of the application does not have options.</td></tr>
<tr><td>Precision</td><td colspan="4">NA</td></tr>
<tr><td>Cost</td><td colspan="4">NA</td></tr>
<tr><td></td><td>MANUFACTURING</td><td>-</td><td colspan="4">The object cannot be converted into a manufacturable file format.</td></tr>
</table>

4.2.3 Component-Based Programs

Modeling in component-based programs is not done by entities, such as lines, circles or 3D shapes; but by 3D components and/or objects representing the major elements of design, such as walls, beams, columns, etc. There are component-based programs that have been especially developed for architects, but they usually have limited capabilities for design development or form generation. ArchiCAD software, a component-based drawing and modeling environment, is an application widely used by architects. The software creates files in PLN file format and has a variety of import-export options.

In ArchiCAD software, the object is drawn by combining components/objects that are previously defined in the extensive library of the software. Although there is a wide range of options regarding the objects in the library, to model a specific shape like a torus, the user has to find a proper object to turn into a torus. In ArchiCAD software, it has been found that the ‘elbow’ object is most suitable for turning into a torus shape. With the necessary parameter modifications, the torus can be modeled in ArchiCAD software from the elbow object in the library.

This type of a torus can be seen in Figure 4.17. It is seen that the object, when converted into a DWG format, is a polygon mesh, which means it is not actually a smooth-surfaced torus but rather a surface mesh. The properties of the torus can be seen in Table 4.12.

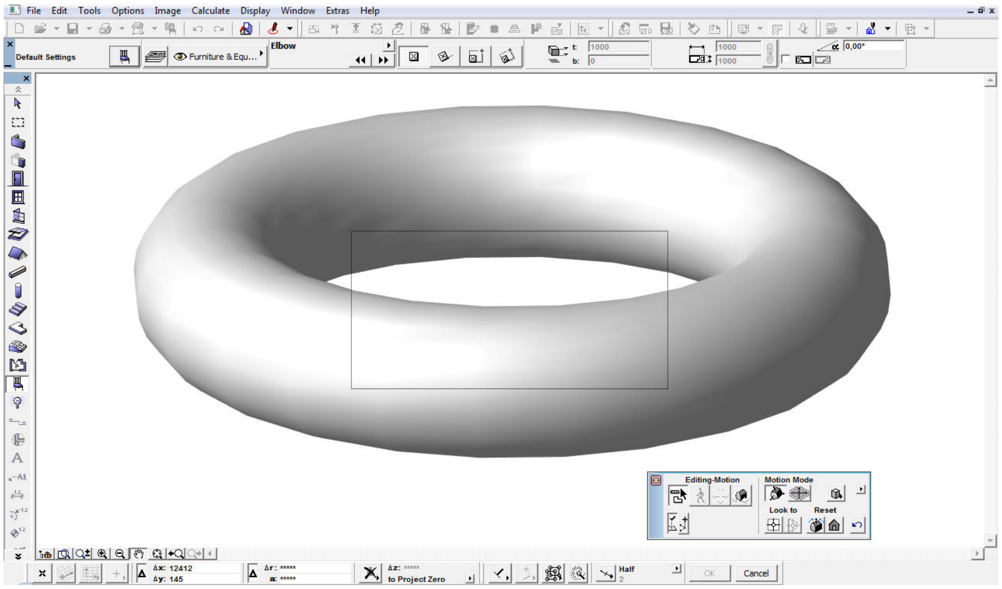
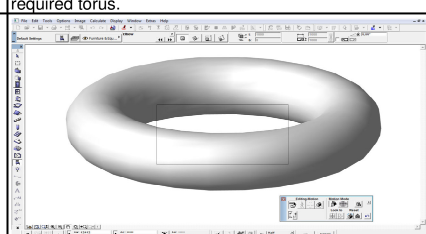


Figure 4.17 The torus modeled from the elbow object of ArchiCAD software.

Table 4.12 Properties of the torus modeled from the elbow object of ArchiCAD software.

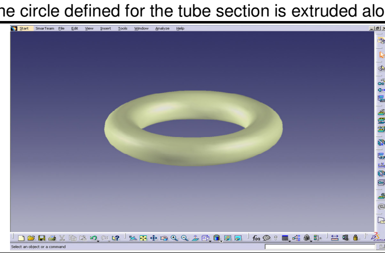
<table>
<tr><td colspan="2"></td><td colspan="5">ArchiCAD (.pln)</td></tr>
<tr><td rowspan="9">SURFACE</td><td>COMMANDS</td><td colspan="5">Objects Library</td></tr>
<tr><td>HOW TO MODEL</td><td colspan="5">In the objects library, within the basic shapes, the ‘elbow’ object is chosen for creating a torus. The dimensions for the elbow and the angle are given in the properties screen of the object to get the required torus.</td></tr>
<tr><td>MODEL PROPERTY</td><td colspan="2"></td><td colspan="3">PROPERTIES
File Format: .pln
Object Type: Polygon Mesh
Units: torus radius 120; tube radius 30; segments 30
Modeling Time: counted in seconds
Modeling Cost: software cost</td></tr>
<tr><td rowspan="3">DATA EXCHANGE</td><td>*.dxf, *.3ds</td><td colspan="4">Data exchange is needed and the object is transformed from a *.pln file into another file format from the export property of the software.</td></tr>
<tr><td>Precision</td><td colspan="4">NA</td></tr>
<tr><td>Cost</td><td colspan="4">NA</td></tr>
<tr><td>MANUFACTURING</td><td>-</td><td colspan="4">The object can be converted into a manufacturable file format, but as long as these cannot be opened by target applications the file cannot be used.</td></tr>
</table>

4.2.4 Design Development Programs

Design development programs are used to develop design schemes in which the structural layout of the model can be obtained. These programs usually enable parametric design, functions for generating digital mock-ups and tool path generation, etc.

For the purpose of this study, CATIA software has been chosen, which is a design development program widely used in the aerospace and automotive sectors for generating design and also for CAM programming. To model a torus in CATIA software, it is possible to use basic modeling commands in a similar way to the previously described applications. The properties of such a torus can be followed in Table 4.13.

Table 4.13 Properties of the torus modeled using the extrude command of CATIA software.

		CATIA (.CATproduct)			
VOLUME	COMMANDS	Extrude			
	HOW TO MODEL	Two circles are specified by the user; one is for the torus and the second is for the tube section. The circle defined for the tube section is extruded along the circle defining the torus.			
	MODEL PROPERTY		PROPERTIES		
			File Format	.CATproduct	
			Object Type	3D solid	
			Units	torus radius	120
				tube radius	30
			Modeling Time	counted in seconds	
			Modeling Cost	software cost	
	DATA EXCHANGE	+	Data exchange can be done if CAM programming will be done in another application.		
		Precision	NA		
		Cost	NA		
	MANUFACTURING	+	The object can be converted in another file format, or the CAM programming can be done within the software		

Commands in the modeling programs have been investigated in the study together with the differences they have in different applications. In Table 4.14, the tori modeled in different program types and their way of creation is listed. According to the data obtained form the models, Table 4.15 has been formed. In the table the properties of each command can be followed in terms of their type of construction according to the applications. During the study the information on this table is obtained as a general perspective of program types and their methods for creating objects. Therefore, the information on the table may not necessarily be correct for every application.

Table 4.14 Program types and the commands used in each to model the torus.

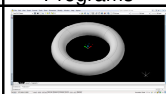
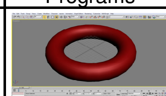
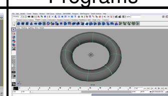
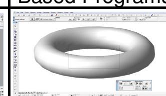
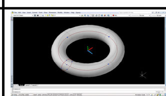
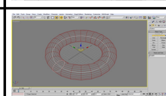
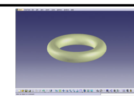
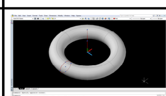
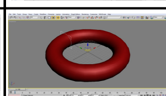
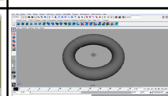
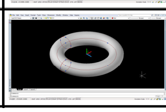
	Entity-Based Programs	Rendering Programs	Animation Programs	Component-Based Programs	Design Devlp. Programs
Object Library					
Extrude					
Revolve					
Loft					

Table 4.15 Properties of the basic commands and their type of constructing 3D objects according to the program types.

			Entity-Based Programs		Rendering Programs		Animation Programs		Component-Based Programs		Design Devlp. Programs	
Command Name	**General Description**	**Type of Production**		**Object Type**		**Object Type**		**Object Type**		**Object Type**		**Object Type**
extrude	add thickness to 2D entities	open cross sections to obtain **surfaces**	+	Surface	+	NURBS Surface Mesh	+	NURBS Surface Mesh	-	-	+	Surface
		closed cross sections to obtain **surfaces**	-	-	+	NURBS Surface Mesh	+	NURBS Surface Mesh	-	-	-	-
		closed cross sections to obtain **volumes**	+	3D Solid	-	-	-	-	-	-	+	3D Solid
loft	create surface/volume between two or more 2D entities	open cross sections to obtain **surfaces**	+	Surface	+	NURBS Surface Mesh	+	NURBS Surface Mesh	-	-	+	Surface
		closed cross sections to obtain **surfaces**	-	-	+	NURBS Surface Mesh	+	NURBS Surface Mesh	-	-	-	-
		closed cross sections to obtain **volumes**	+	3D Solid	-	-	-	-	-	-	+	3D Solid
revolve	rotate 2D entities around an axis to create 3D surface/volume	open cross sections to obtain **surfaces**	+	Polygon Mesh Surface	+	NURBS Surface Mesh	+	NURBS Surface Mesh	-	-	+	Surface
		closed cross sections to obtain **surfaces**	+	Polygon Mesh	+	NURBS Surface Mesh	+	NURBS Surface Mesh	-	-	-	-
		closed cross sections to obtain **volumes**	+	3D Solid	-	-	-	-	-	-	+	3D Solid

4.3 Data exchange

Modeling is the first step in the manufacturing of a designed object using CAD/CAM technology. Computer-aided manufacturing (CAM) requires tool path programming for the production of the model. If the manufactured product (and thus, the tool path programming) is to be as accurate as the visual representation of the model on the screen, the model has to have completely defined data of its 3D geometry.

The modeling environments described in the previous section are not compatible with machining languages, and therefore the model data have to be converted into a CAM programming file format before the torus can be manufactured. There are several ways for data exchange (Figure 4.18). The conversion can be done using the import-export properties of each application, but usually, as the different applications have different file properties, the import-export process gives results that do not satisfy manufacturing needs. There may also be incompatibilities between the modeling and programming environments that do not allow the support of each other's file formats. This incompatibility among applications has made it necessary for the creation of data exchange file formats and/or environments.

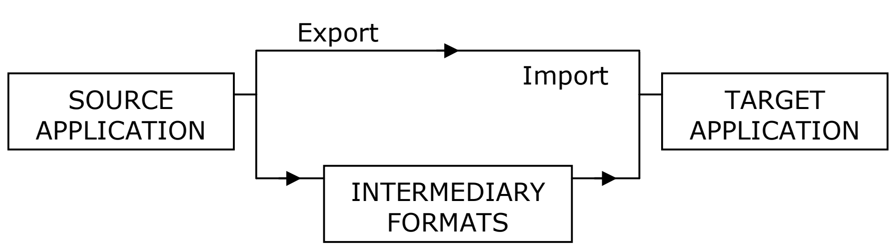


Figure 4.18 The data exchange process.

Data exchange in CAD/CAM is a necessity, as applications do not store data in the same way, and the respective file formats are not compatible with method of data storage of other applications. The complexity of CAD/CAM systems, the varying user requirements and the incompatibility among entity representations can be counted as being among the driving forces behind the concept of data exchange[3]. CAD/CAM systems require mathematically well-defined objects for the accurate manufacturing process, and as not every CNC environment supports every file format for the model data, there is the need for the transformation of information.

There are four data types that are needed to be transformed between CAD/CAM systems: first is the shape data, which has both geometric and topological information, second is the non-shape data, such as shaded images and measuring units; third is the design data, which includes information for analysis purposes such as mass property; and the final type is the manufacturing data, which includes the information for tooling, NC tool paths, etc[4].

Some CAD systems can import/export these data types from/to other CAD formats, but usually an intermediary format is needed for conversion as described above. In such an exchange process the data from the source file is preprocessed to a standard neutral file, and later post-processed to the target system. In some cases, due to the inconsistencies between applications/versions of applications etc., exporting files from one format to another may not be possible. As a great loss of information may occur, or some data may become corrupt, the data cannot be read accurately by the target system. To overcome this, pre/post processors work as intermediary formats, but often even the data processors cannot store the model data completely.

Each CAD system has its own definition of geometry, and they differ both mathematically and structurally, so there is always some loss of information when

[3] Data Exchange Between CAD/CAE/CAM Systems

[4] Ibid.

translating data from one CAD data format to another. The intermediate file formats usually have limited abilities for translating types of data, which can be interpreted differently in different systems. Therefore, it is important to identify the required data to be translated during data exchange[5]. There are even aspects that should be considered when only the 3D model is to be translated, for example, whether the model is wire-frame, surface or solid, the topology information, face and edge identifications, feature or history information of the model, etc. The type of data storage of the two systems between which data exchange is to take place is also important. The definition of the model in the source system may not be in a form that the target system can understand, resulting in a loss of information.

There are several steps to be taken when data exchange is to take place using intermediary formats (neutral file exchange formats). First, the model data is to be converted into one of these formats, either by exporting or by using a data exchange environment. When the data is pre-processed to a neutral file, it is then read by the target system, post-processing the read data into a format readable by the application program[6]. As every CAD system has different file extensions/file format types for the documentation of the files created by it, there are highly recommended file extensions in between CAD/CAM environments, patented to companies owned, but generally used, such as:

3DS (3d graphics file)
DGN (MicroStation design file)
DWG (AutoCAD drawing file)
MOD (CATIA model file)

[5] http://en.wikipedia.org/wiki/CAD_data_exchange (December 2007)

[6] SCHODEK, Daniel; BECHTHOLD, Martin; GRIGGS, Kimo; KAO, Kenneth Martin and STEINBERG, Marco. *Digital Design and Manufacturing: CAD/CAM Applications in Architecture and Design.* John Wiley & Sons, INC. 2005.

PRT (SolidWorks and UGS NX model file)

File formats of different applications have their own definition of geometry (datum) that is usually incompatible with other file formats. The allowances/capacities of intermediary formats also differ. It is therefore necessary to identify at least the intermediary formats (standard neutral data formats), according to their basic properties in order to understand data exchange and the way it is considered by each format.

DXF (Drawing Interchange Format)

The DXF extension is one of the most commonly used data exchange formats in solid modeling programs, originally developed by the Autodesk group. This kind of file supports two-dimensional line entities, surfaces and solids but cannot store or support NURBS[7]. Some design development environments allow users to import 2D DXF files, use them as native drawing entities, and export them for paper documentation[8].

IGES (Initial Graphics Exchange Specification)

"IGES establishes information structures for digital representation and exchange of product definition data. It supports exchanging this data among CAD/CAM systems."[9] This is a standard for the display and documentation of graphic documents between different computer-aided design systems[10]. Using IGES, product data models in the form of circuit diagrams, wire-frame, free form surface or solid modeling representations can be exchanged. Applications supported by

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[7] Ibid.

[8] Ibid.

[9] http://www.uspro.org/documents/IGES5-3_forDownload.pdf (p. 1) (December 2007)

[10] SCHODEK, Daniel; BECHTHOLD, Martin; GRIGGS, Kimo; KAO, Kenneth Martin and STEINBERG, Marco. *Digital Design and Manufacturing: CAD/CAM Applications in Architecture and Design.* John Wiley & Sons, INC. 2005.

IGES include traditional engineering drawings, models for analysis, and other manufacturing functions[11]. "IGES files support a larger range of entities than DXF files and are commonly used in transferring 3D geometry from CAD systems to CAM modules."[12]

STL (Stereolithography or Standard Triangulation Language)

STL is another file format used for data transfer. STL files must be written from solid models as they involve the triangulation of solid faces[13]. Within STL files only the surface geometry of 3D objects are described, without other CAD attributes[14].

Data exchange using these or any other format is a part of today's digital design and analysis world, but there are limitations due to the formats. These usually reduce the information of the original model to standardized descriptions or entities. The imported models/shapes, being static, cannot be edited. The exchange system usually works correctly for simple geometric entities, but as the geometry becomes more complex, errors and losses of information increase.[15]

In CAD/CAM applications, the aim is to be able to manufacture a digital model so that the resulting object is as accurate as the digital model itself. When precision, the minimization of waste material, and the lowering of computational and labor costs are important issues, then it can be seen that the loss or incompleteness of data while exchanging formats becomes a severe problem.

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[11] http://en.wikipedia.org/wiki/IGES (December 2007)

[12] SCHODEK, Daniel; BECHTHOLD, Martin; GRIGGS, Kimo; KAO, Kenneth Martin and STEINBERG, Marco. *Digital Design and Manufacturing: CAD/CAM Applications in Architecture and Design.* John Wiley & Sons, INC. 2005.

[13] Ibid.

[14] http://en.wikipedia.org/wiki/STL_%28file_format%29 (December 2007)

[15] Ibid.

Another standard data exchange format, known as STEP (Standard for the Exchange of Product Model Data), has some important conceptual differences from IGES or DXF files[16]. STEP supports any industrial application, including mechanical, electric, plant design and architecture and engineering construction. It has the ability to exchange a digital model, with its all supporting information, including the four types of product data (shape, non-shape, design and manufacturing data)[17].

Data exchange is an essential requirement since there is no single standard data storage system that is compatible with all data types. Differences among the capabilities of applications demand the designer to use a variety of programs. When the design data are transferred from one system to another, the data can change or be damaged preventing transferred data from being read by target system.

In the following chapter, the model data obtained so far for the torus object have been examined to discover whether the data are compatible with CAM programming or not. Thus, data exchange has been investigated within the case study and it has been decided that tool path generation is to be carried out using UniGraphics software, which is a design development program enabling CAM programming. The actual manufacturing process for the torus is also illustrated in the next chapter.

[16] Ibid.

[17] Data Exchange Between CAD/CAE/CAM Systems

CHAPTER 5

CASE STUDY PART II: COMPUTER-AIDED MANUFACTURING

In this chapter, it is aimed to illustrate the CAD/CAM sequence subsequent to the modeling of the object-torus, and to point out how the modeling methods affect the production process, and thus the end product. Within the context of the present study, first, data exchange has been studied. Although this process has been studied on a defined object-torus, the problems encountered are not case specific, and give a general perspective of the requirements, progression and outcomes of a CAD/CAM system. In Figure 5.1, a general list of the CAD/CAM systems and their requirements can be seen.

Data exchange, which has been explained in the previous chapter, is an important aspect of digital manufacturing. The modeling environments, familiar to architecture, have been investigated in the previous chapter in terms of their properties in modeling and types of data storage. The model data obtained from these programs have to be transformed into CAM programming software in order to generate instructions for the programming of CNC machining (tool path generation).

Design development programs usually contain CAM modules in which the tool path generation can be declared. Therefore, it is necessary to transform files that have been modeled in other programs to such modules. The required steps for data exchange and the potential problems that may arise during data exchange have been investigated in the study.

Tool path generation is another aspect that should be considered in CAD/CAM, which is usually carried out by trained operators. In this process, it is necessary to have a solid knowledge of CNC machining, the cutters and types of CNC, etc. in order to acquire the appropriate instructions for machining. The process of CAD/CAM, from the initial design to tool path generation, and then to the actual machining, has been observed and documented in the study.

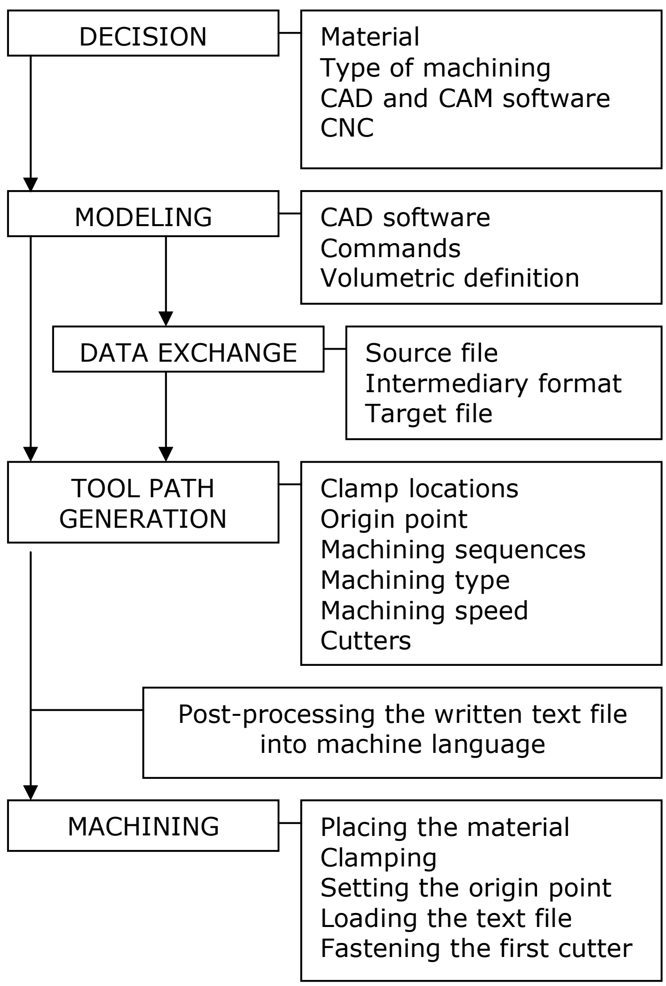


Figure 5.1 CAD/CAM system, its requirement and important aspects.

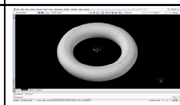
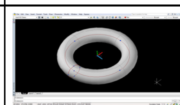
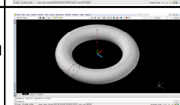
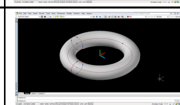
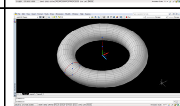
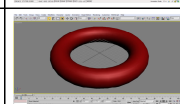
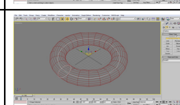
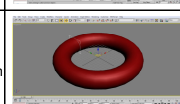
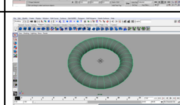
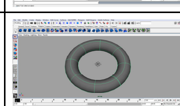
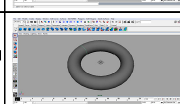
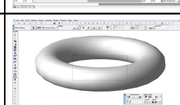
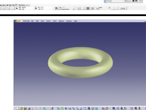
5.1 Data Exchange Process for CAM

For the case study, the torus object has been modeled in various CAD applications. For the programming of CNC machining, the models are to be transferred into standard neutral data formats to be post-processed to the design development programs.

In some programs such as AutoCAD and 3ds Max, the programs have a variety of export options so that the files created in the program can be converted into other file formats. In AutoCAD, for example, it is possible to export the DWG file into a STL, SAT or DXF file format, which are intermediate data formats used for data exchange. However, the export option does not necessarily create files that are compatible with target programs. For example, the STL file exported from the DWG file may not be read by UniGraphics software, which is a design development program that can read data from STL files.

It has been seen that export options of the programs do not always convert files with enough accuracy to be read by other programs. Some programs do not even have export options for intermediate formats. There are certain conversion programs, in this respect, which can be used to convert some file formats into formats that are compatible with the process of interest. During such a file conversion, by using data conversion programs the data in the source file are reduced into standardized descriptions of intermediary formats. When such files are post-processed to other programs, the loss of information can be observed. For the files to be used in such a case, the data have to be corrected, which in some cases can be a more complicated process than the remodeling of the object. In this study, for example, to model tori in one of the applications described above has been completed less than a minute. However, during the study it has been spent several weeks to find a proper way to post-process the data obtained in the CAD applications to the CAM programs, which resulted unsuccessfully for all the tori except the one modeled in the design development environment.

Table 5.1 The comparison table to map the most common solid modeling methods and their conversions, if possible, to be accessed by CAM systems.

	CAD	software	file format	types of model	type of construction commands	Image	cost & time	data exchange	CAM
1	Entity-Based Drafting Program	AutoCAD	DWG	**volume**	**library object**		NA	*.sat, *.stl, *.dxf	Data could **not** be used for CAM.
2	Entity-Based Drafting Program	AutoCAD	DWG	**volume**	**extrude** a circle along a circular path		NA	*.sat, *.stl, *.dxf	Data could **not** be used for CAM.
3	Entity-Based Drafting Program	AutoCAD	DWG	**volume**	**revolve** a circle around an axis		NA	*.sat, *.stl, *.dxf	Data could **not** be used for CAM.
4	Entity-Based Drafting Program	AutoCAD	DWG	**volume**	**loft** two circles along a circular path		NA	*.sat, *.stl, *.dxf	Data could **not** be used for CAM.
5	Entity-Based Drafting Program	AutoCAD	DWG	**surface**	**revolve mesh** a circle around an axis having the values of 30 for meshes		NA	*.dxf	Data could **not** be used for CAM.
6	Rendering Program	3ds MAX	MAX	**surface**	**library object**		NA	*.dxf, *.3ds	Data could **not** be used for CAM.
7	Rendering Program	3ds MAX	MAX	**surface**	**loft** (extrude) a circle along a circular path		NA	*.dxf, *.3ds	Data could **not** be used for CAM.
8	Rendering Program	3ds MAX	MAX	**surface**	**lathe** (revolve) a circle around its pivot location		NA	*.dxf, *.3ds	Data could **not** be used for CAM.
9	Animation Program	MAYA	MB	**volume**	**library object (polygon)**		NA	-	Data could **not** be used for CAM.
10	Animation Program	MAYA	MB	**surface**	**library object (NURBS)**		NA	-	Data could **not** be used for CAM.
11	Animation Program	MAYA	MB	**surface**	**revolve** a circle around an axis		NA	-	Data could **not** be used for CAM.
12	Component-Based Program	ArchiCAD	PLN	**surface**	**library object**		NA	-	Data could **not** be used for CAM.
13	Design Development Program	CATIA	CATproduct	**volume**	**extrude** a circle along a circular path		NA	+	Data exchange **could be done.** Data can also be used in the CAM module of the same software.

The problems discussed above on the torus model are summarized in Table 5.1 showing how different methods are employed in obtaining the solid model together with the problems encountered in data conversion for manufacturing process within a matrix of comparison.

5.2 Manufacturing Process

5.2.1 Digital Modeling for CAM

As was described in the previous chapter the object torus has been modeled in several CAD applications. It has been intended to manufacture these torus models in order to observe the differences caused by the variations among the modeling environments and modeling methods and commands. As there have been obtained several types of tori, it has been expected varieties in the manufacturing process and thus, in the manufactured objects. However, as shown in Table 5.2, due to the difficulties encountered in data conversion, it has become problematic to use the models for CAM process. Only the torus modeled in the design development program (CATIA) could have been post-processed to the CAM program (UniGraphics). Therefore the problem of how modeling method affects the manufacturing process has been resolved by using the CAM program to model the tori together with the torus modeled in CATIA.

Finally, it has been decided to manufacture three tori to observe the differences that are encountered in the CAM process. Hence, it has been decided to first use the torus modeled in CATIA, since data exchange is possible between CATIA and UniGraphics software (both being design development environments). The other two tori are modeled using UniGraphics software, which will also be used for CAM programming.

Among the three tori, the first torus was modeled using UniGraphics software; and the second in CATIA software and then post-processed to UniGraphics software. These two tori have been modeled using the extrude command of both programs with the same geometrical input. However, subsequent to data exchange between systems, it is seen that the two tori are not the same, having visible differences on their surfaces. This difference can be seen in Figure 5.2. As the first torus has one continuous surface, the post-processed torus has several surface patches on its body. Although the previous model in the source program had a continuous surface, the model data had been corrupted after data exchange.

The third model/torus is again modeled using UniGraphics software, but this time, instead of using circles to model the torus, polygons with 20 sides are used. This variation has been made in order to observe the surface differences in the manufactured model (Figure 5.2). The third torus tires to simulate the condition of what the end result would be if one of the previously modeled tori that had a segmented body instead of a smooth circular surface could have been imported to the CAM program for manufacturing.

The three tori were placed side by side within a box-like object for the ease of production and comparison. The CAM programming was also carried out accordingly, which means the actual object to be manufactured has been the three tori submerged into a box (Figure 5.2). For the actual CAM operation, it has been decided to use a 5-axis milling machine among several other types of CNC that could have also been used. The production method of such a machine (5-axis milling machine) is subtraction, which is removing material from the model. Therefore a cover box has been modeled in the CAM program to simulate the actual material that the model is to be subtracted from.

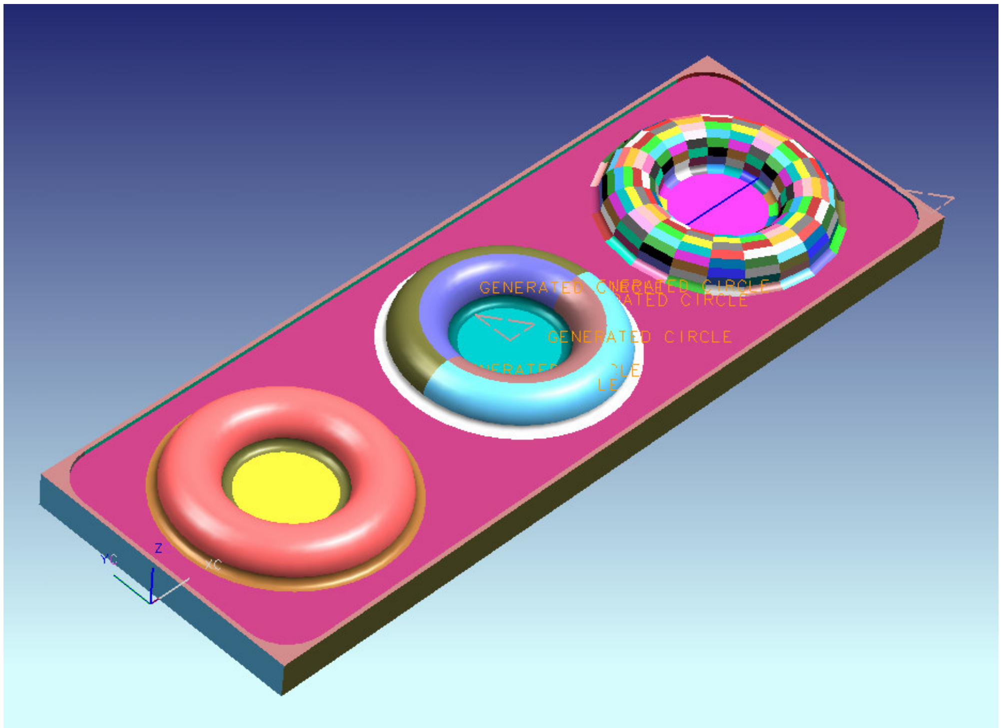


Figure 5.2 The actual model to be manufactured. The one on the left is modeled in Unigraphics software, the one in the middle is post-processed from CATIA software and the one on the right is modeled from 20 sided-polygons.

5.2.2 Tool Path Generation

As it has been decided to use a 5-axis milling machine for the machining of the torus object, which is to be formed from aluminum, tool path generation has been made accordingly. Programming of the machining is done while the CAM program identifies the geometry of the solid model. According to the decisions concerning the properties of the machining are given by the programmer, the program generates the tool path for the machine head movements for the operation. For tool path generation (CAM programming) it must be decided, first of all, in what sequence the machining of the object is to be done. Accordingly, the properties of the cutters, the machining speed and other properties of each machining sequence have to be decided according to the model.

In the case of the torus modeled for the study, the machining has been programmed in several different sequences. These can be followed in Figure 5.3. In the first steps tool path has been generated for the machining of the available material to the size of the model. The material chosen is not necessarily the same size as the model so the material has to be machined to the specified size (Figure 5.4). Within this process the clamps that will hold the object during machining have also been considered and the programming has been done according to the clamp locations, which have been changed during machining for the manufacturing of all the parts of the object.

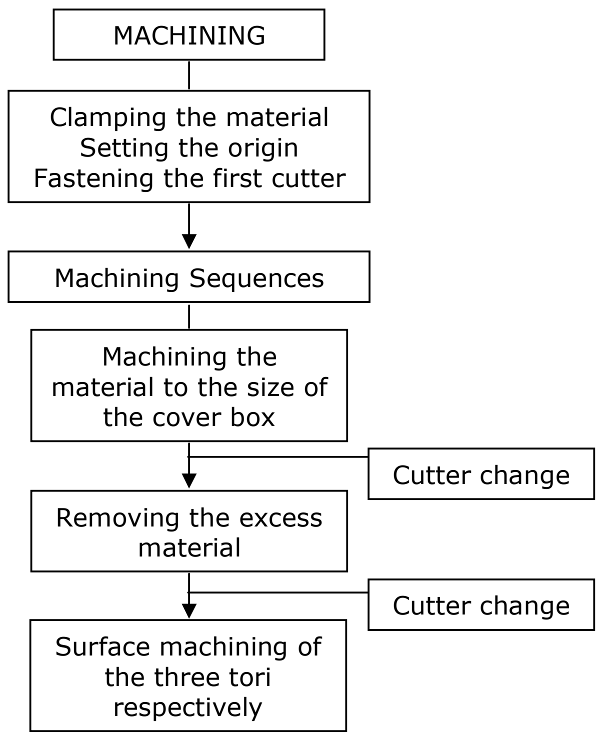


Figure 5.3 Machining sequences of the studied object.

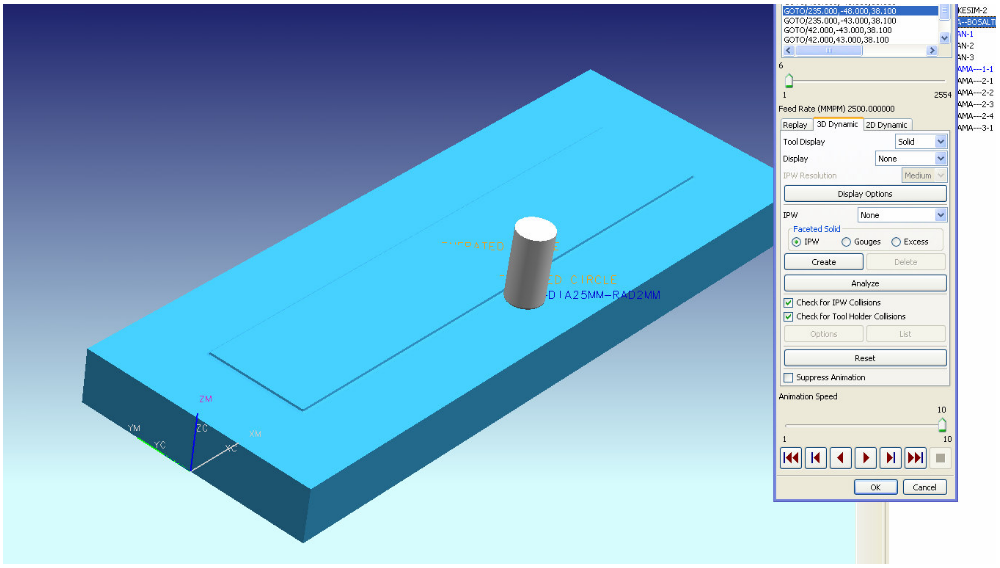


Figure 5.4 The simulated model of the first machining steps; preparing the material to the size of the object.

Following sequences of the machining included the removing of the excess material out of the object, which is done until the surface corrections of the model (Figure 5.5). The surface corrections of the box and the three tori have been programmed later while associating different types of cutters to the manufacturing.

For the machining of the surfaces of the model, the faces of the solid model are selected and every face has been programmed accordingly. In the example of the first torus, as it has one continuous surface, whole surface is identified by the program at once and the tool path has been generated accordingly. In Figure 5.6 the simulation of the surface machining of the first torus can be seen.

Tool path generated for the second torus necessitated the identification of the four surface patches of the torus face by the CAM program. These four surface patches have been selected one by one and the programming has been generated accordingly. Figure 5.6 show the simulation of the machining of one of the surfaces of the second torus. As the tool paths have been generated separately, the programming of the torus is completed when all the four surfaces are identified by the CAM program.

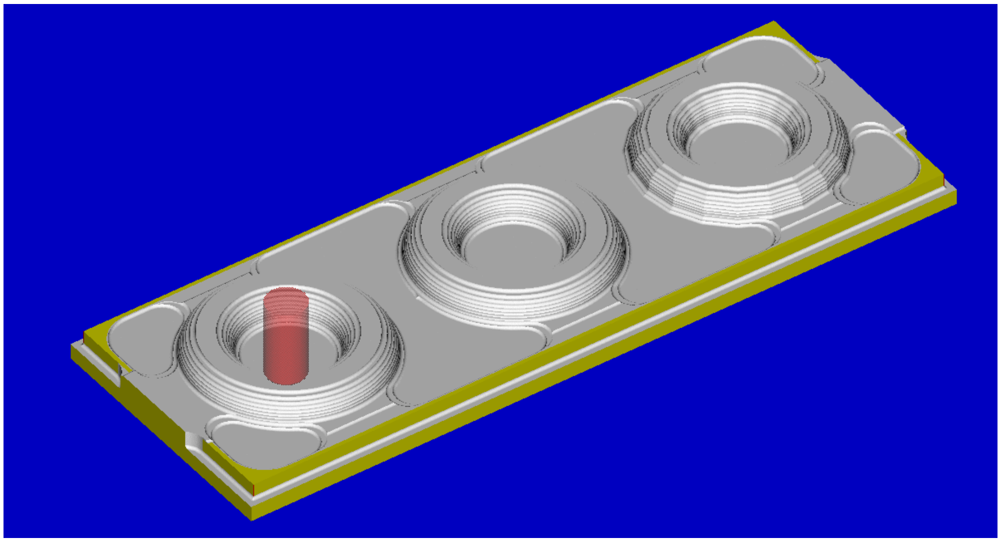


Figure 5.5 The simulated model of the removing of the excess material of the model.

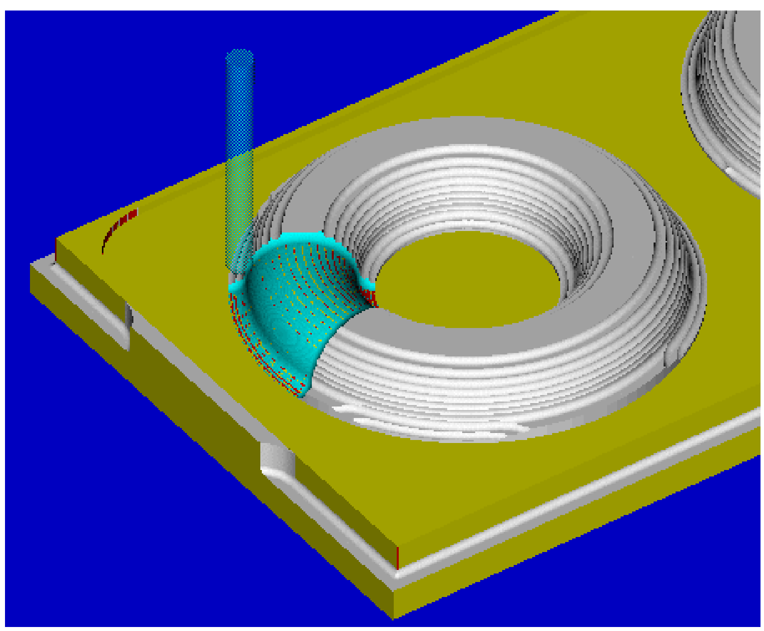


Figure 5.6 The simulated view of the surface machining of the first torus.

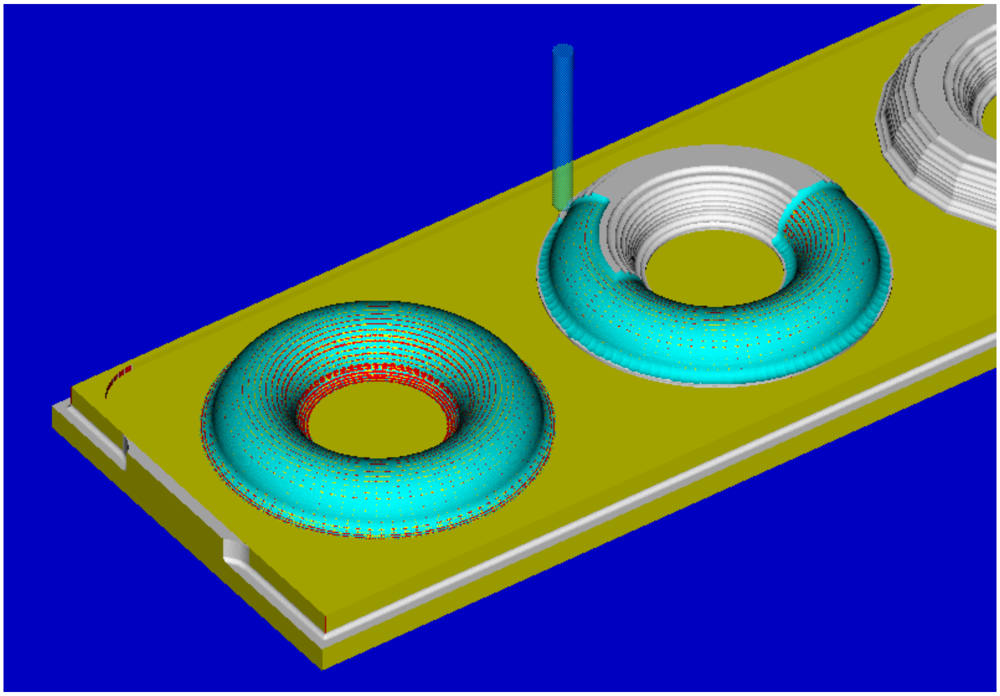


Figure 5.7 The simulated model of the machining of the third surface of the second torus.

The final step, being the machining of the polygonal torus, has been programmed using a different method. As the torus is made of too many surface patches, machining is not programmed according to the selected surfaces but to an area of surfaces. Figure 5.8 shows the simulated view of this kind of machining process.

In each sequence of machining, not only the areas to be milled, but also the cutters, the machining speed of the machine head and other machining properties have been programmed. A total of three different cutters are used in the process for different steps of manufacturing. The cutter used for removing the excess material is different to the cutter that is used to obtain the surface quality of the tori. The machining speed has been programmed according to the parts of the model and the allowances of the CNC.

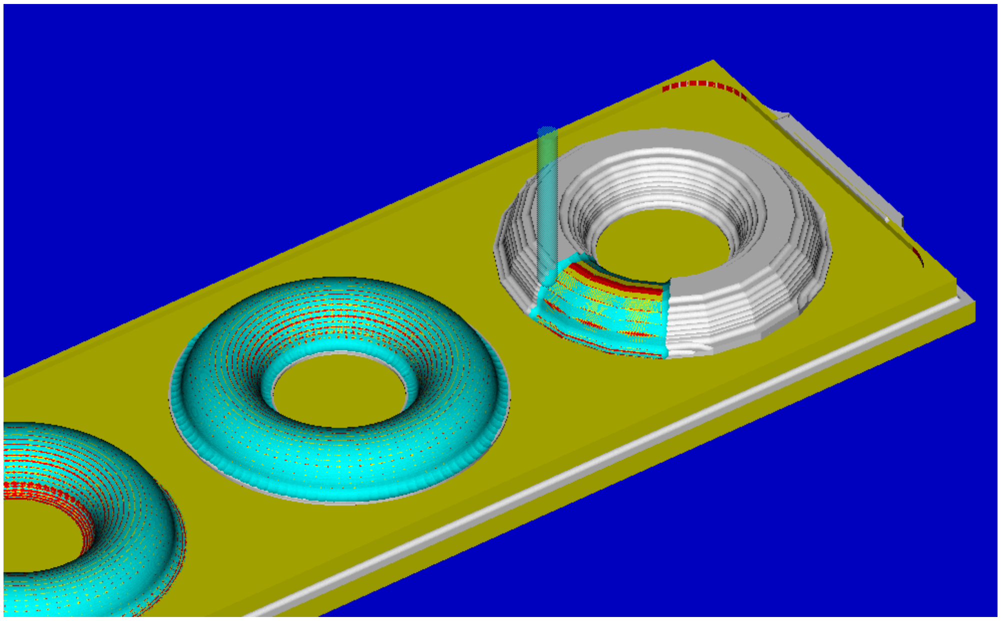


Figure 5.8 The simulated model of the machining of the third torus.

Following the programming for CAM application, a text file is created in which the coordinates of the cutting arm in 3D i.e. x, y, and z coordinates together with data of types of cutters, machining speed and time for machining are defined. The text file obtained through this process requires further post processing in order to be converted into machine language, which will enable the solid model to be manufactured. The post-processing of the text file is done within the CAM module, and is a short process completed in seconds. When the text file of the machine head movements is created according to the CNC, the file is sent to the machine table for the actual manufacturing.

5.2.3 CAM Process

The final step in CAD/CAM is the actual machining operation. The operation begins with the preparation of the CNC. The material, out of which the model is to be manufactured, has been clamped to the manufacturing board, and the origin point (0,0,0) has been set. The origin has been determined during tool path generation, since the geometry of the model is identified according to the coordinate system having its origin at the determined point. The origin point has been set for the machine head to identify the model in space.

Following the settings, the text file obtained from the post-processing to the machine language has then been uploaded to the computer of the machine to control the operation (CNC). When the first cutter has been fastened to the machine head, the operation begins. The clamping of the material and the initial part of the operation can be seen in Figures 5.9 to 5.15.

The text file obtained from CAM programming also includes time data, i.e. the approximate time necessary for the completion of the operation. The time assumption is done according to the speed of the operation specified by the programmer and the machine head movements. The operation was completed within approximately four hours, which was consistent with the time estimated by the CAM programming.

The manufactured object can be seen in Figure 5.16.

5.3. Documentation and Results – Comparison/Analysis

The whole process, from modeling to the production, has been documented. The most time consuming, as well as the most difficult step in the whole study, was found to be the time required to export the files from the CAD programs to the CAM programs. Although it is possible to find proper post-processing programs to realize such conversions, it is seen that such processes require much more time than the modeling itself. Also, their computational cost, and thus the production costs are much higher than the solid model itself. Therefore, instead of modeling programs, design development programs have been used for modeling, together with CAM programming.

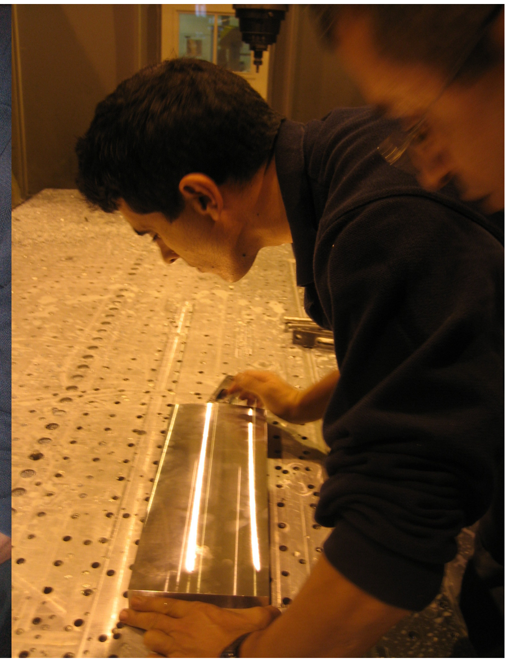


Figure 5.9 and **Figure 5.10** Clamping of the material to the manufacturing board.

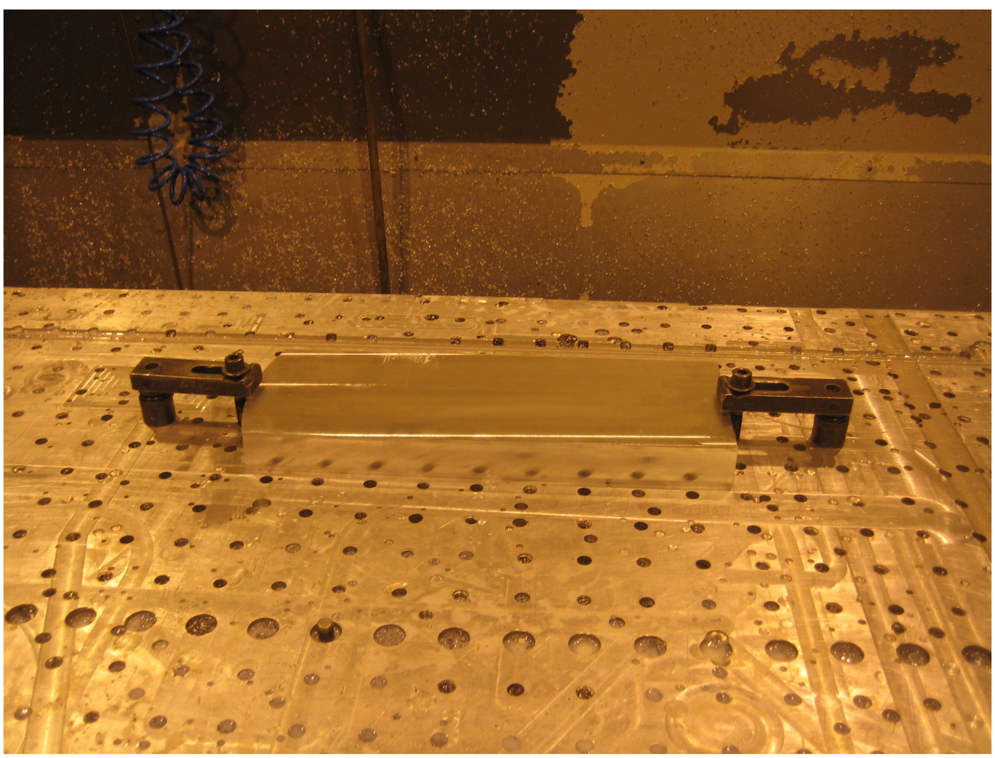


Figure 5.11 The material clamped to the manufacturing board.

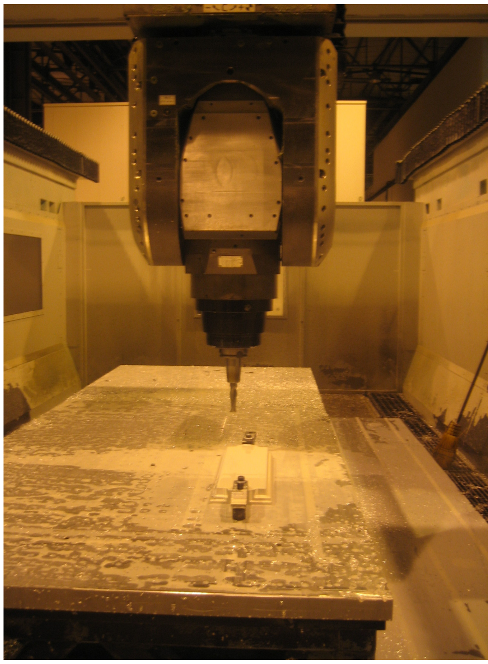
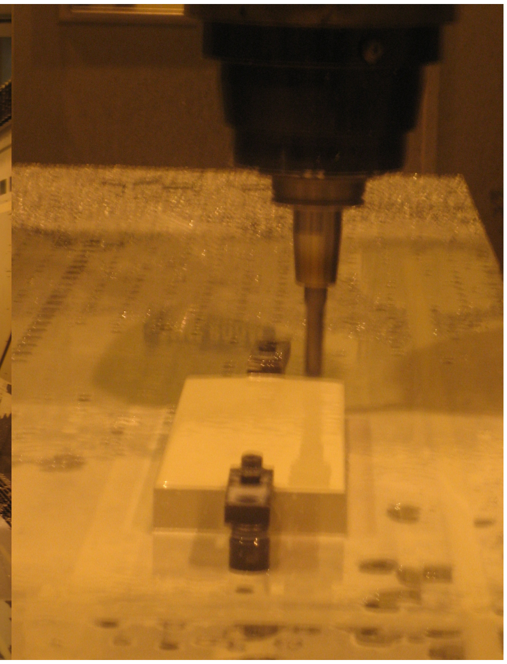



Figure 5.12 and **Figure 5.13** Beginning of the operation.

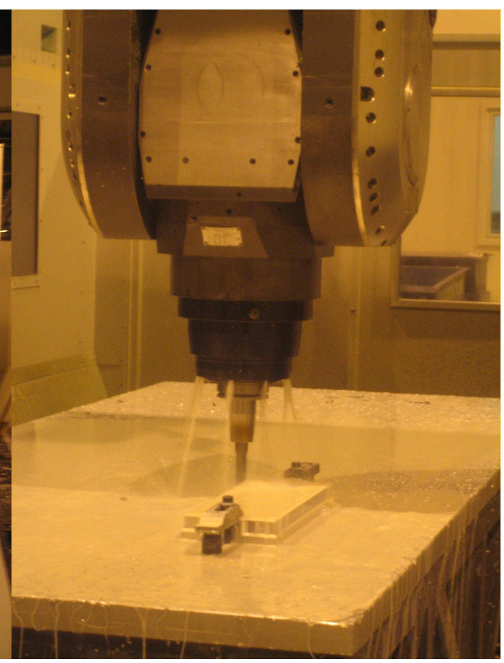



Figure 5.14 and **Figure 5.15** The operation.

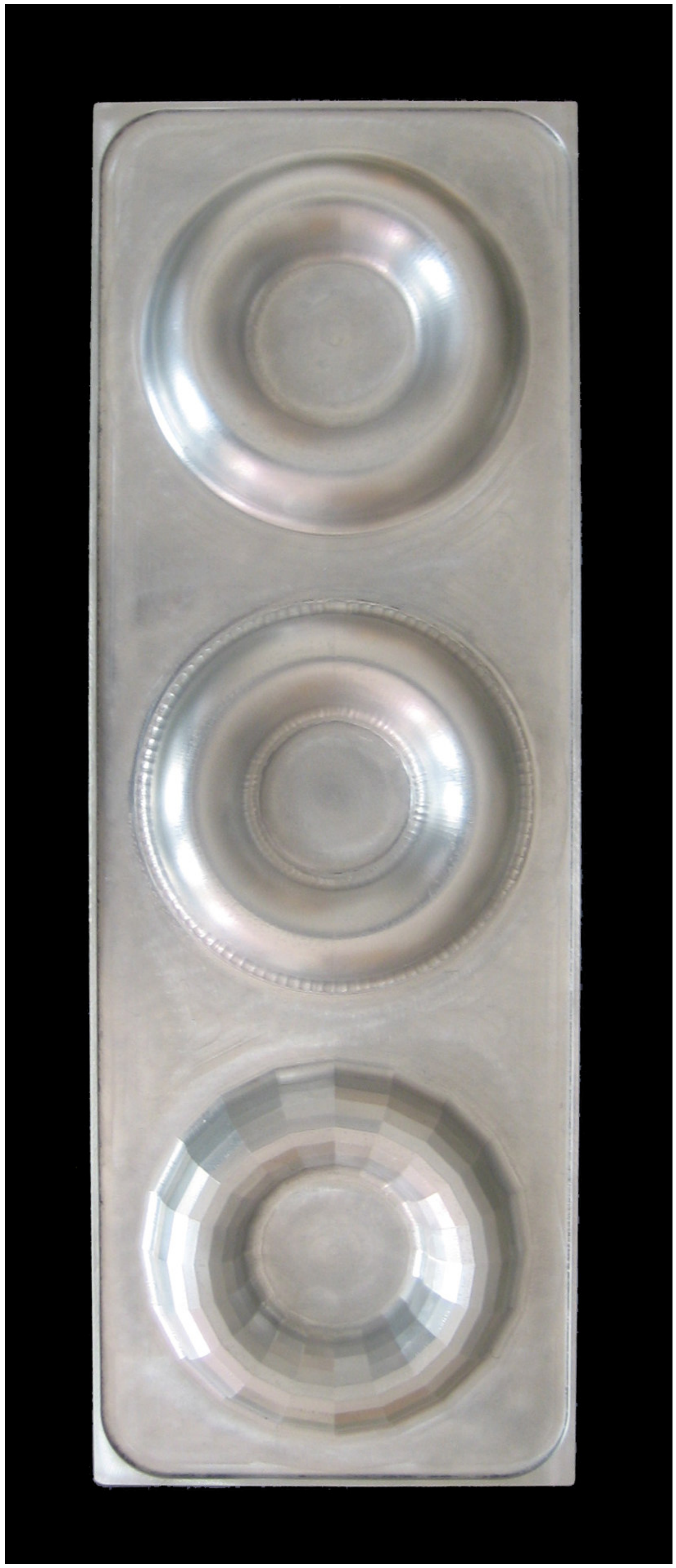


Figure 5.16 The manufactured tori.

After the completion of the digital model and data exchange processes, the CAM programming has been carried out. During CAM programming, not only the digital model itself, but also the initial shape that the model is to be subtracted from, have to be identified. The initial shape of the model should be decided according to the material available.

The experience and the knowledge of the programmer play an important role in selecting the machining processes, as well as in the selection of cutters and other properties related to machining. It is necessary to know and understand the properties of the machines and cutters in order to be able to make the right decisions. This is actually the work of an engineer, rather than of an architect, but the perfect solution requires collaboration between the two fields. The architect does not necessarily have to know CAM programming and its tools, however s/he does need to understand the way CAM programming is carried out, as well as its properties and requirements from the digital model. In this sense, the most essential part of digital fabrication is the collaboration of CAD and CAM systems.

The programming has been completed in approximately three working days, and the entire process, form digital modeling to completion of manufacture took less than a week. Once programming has been completed, an infinite number of models can be manufactured from the same program, making it evident that such CAD/CAM applications are suitable for mass production.

The programming (tool path generation) is carried out according to the model. The programmer is not required to locate every point on the model, but rather an area of points for the program to analyze and identify the 3D model and generate the tool paths. Thus, while parametric changes in the model do not affect the work carried out for programming, they affect the tool path generated by the program. This enables the requirements of mass customization to be indifferent from the requirements of mass production. Therefore, it can be said that CAD/CAM applications are also suitable for mass customization.

After the CAM process, the object has been examined. As the digital models of the three tori had different surface qualities, the same variety can be expected on the manufactured models. In the digital model, the first torus had one continuous smooth surface. It has been seen that the manufactured torus from this first digital model has also a smooth surface, without evidence of cuts, discrepancies or irregularities (Figure 5.17). Similar results can be observed for the other two tori. The second torus has the evidence of surface patches, similar to the digital model, on its body, as can be clearly seen from a closer view shown in Figure 5.19. Figure 5.18 shows the second torus. Third torus is shown in Figure 5.20. Being a segmented torus, the surface property can clearly be observed from the manufactured model.

As a result, it can be said that in each case, CAM can produce the CAD model with great accuracy, meaning not only producing smooth and clear surface qualities but also, if it is necessary, surface differences that can be followed within millimeters. It has been fairly well demonstrated that CAD/CAM technology can produce a digital model with the highest precision, so long as the user obeys the rules of modeling demanded by CAD/CAM. As has been said before, the collaboration between the parts of the system is the most essential requirement in providing the optimum solution. The decisions on the CAD and CAM systems should be made in the initial phase of design process, as every step taken affects the next step in the system.

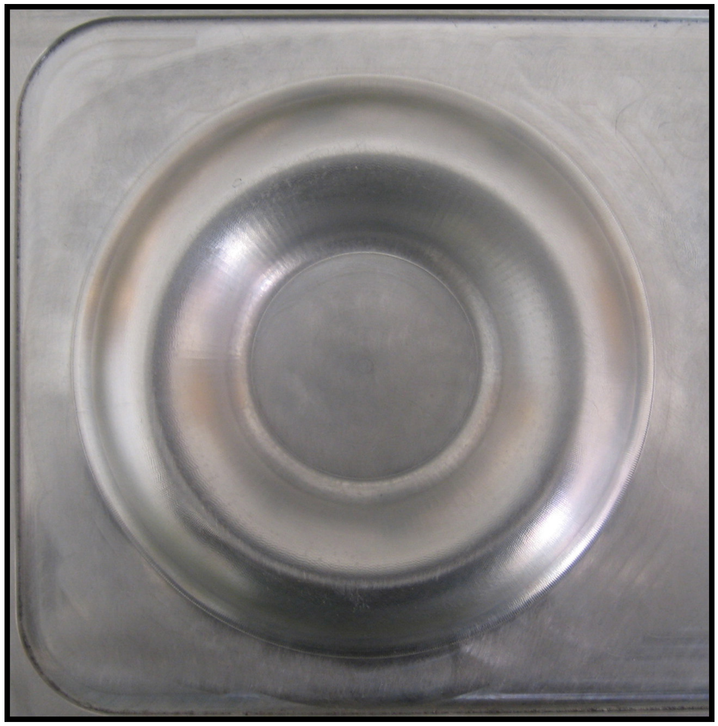


Figure 5.17 First torus without irregularities.

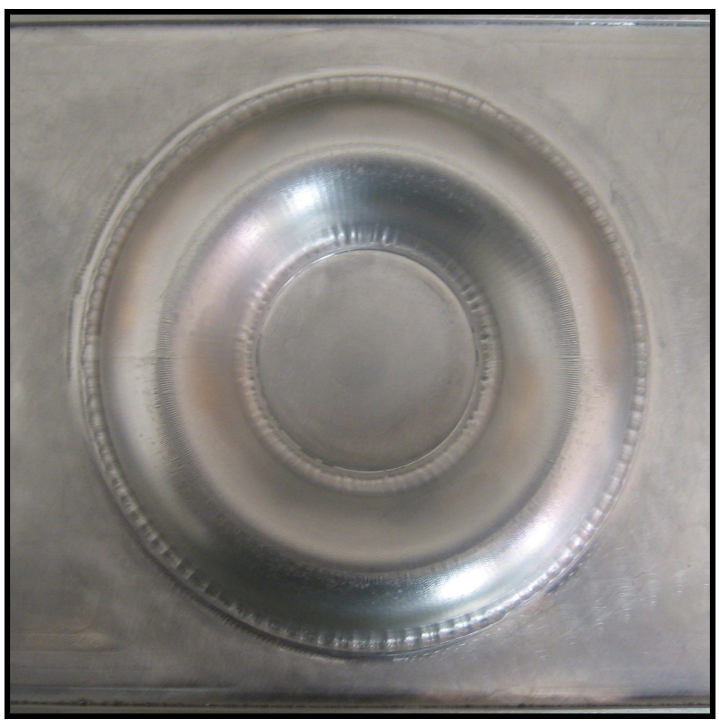


Figure 5.18 Second torus.

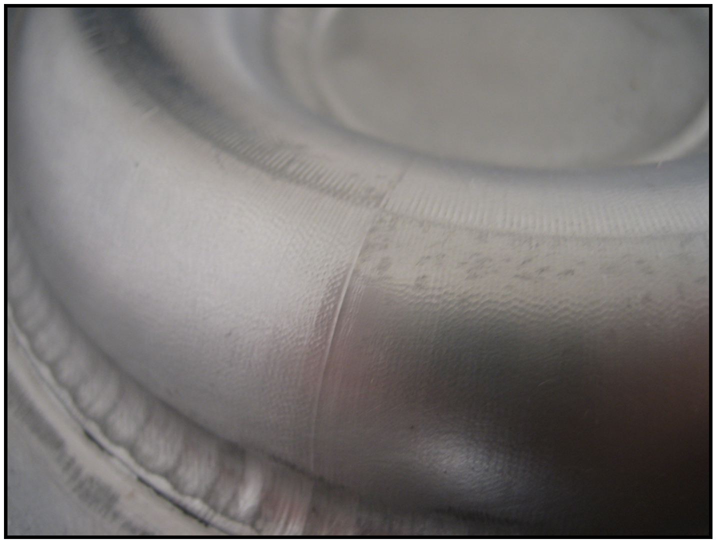


Figure 5.19 Closer view to the surface of the second torus.

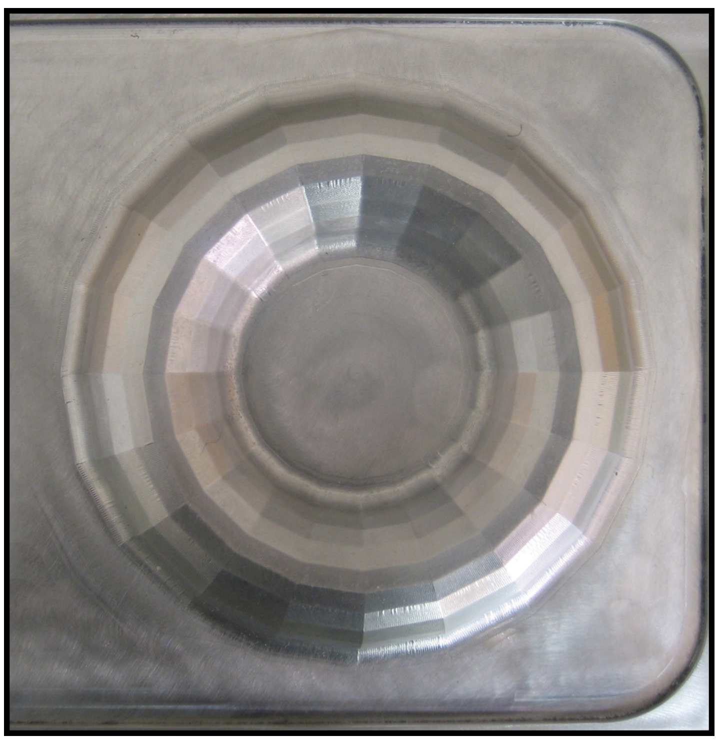


Figure 5.20 Third torus.

CHAPTER 6

CONCLUSION

"Freedom of form, however, implies more responsibility for the designer to choose wisely among the infinite possibilities. The digital manufacturing era, when reality is merely a different output device, is only beginning now. It will truly be an epoch of plenty when mankind will be really able to shape his environment, in all its complexity, in his image."[1]

6.1 Observations – What to Expect from Architectural Design and CAD/CAM Integration

Architects play the leading role in the realization of building projects. Taking a building project as a whole, from the initial concept design to the last phases of construction, the lead architect should supervise the entire process. Architectural design can be a creative work in which the architect talks with his/her own imagination; however the realization of a project requires more than just creative imagination; and that is why architecture and architectural design can never be considered apart from the engineering works and the accompanying technology. Design should always be supported by these means.

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[1] HESSELGREN, Lars. "Design at all Scales" in *Blurring the Lines*, (p. 16-27) ed. André Chaszar. Wiley Academy, 2006. (p.27)

The entire building process begins with the conceptual design idea, and continues with the realization of the design until the actual construction phase ends. Every element of design has an affect on the rest of the process. When the architect decides upon a design part, it has to be in collaboration with the overall process. As has been observed in the study, the CAD/CAM system has a similar requirement, in that the CAD product affects the CAM product. With this in mind, the architectural model should be considered accordingly when digital fabrication is involved.

Since the very invention, computers have been used as aids to many tasks, from adding/subtracting to much more complicated engineering works. The objective behind the invention of the computer at its very beginnings was to satisfy the need of man for a machine that could ease his daily works. Today, as technology develops day by day at incredible speed, it is now possible to handle the most complicated tasks with an inconceivable ease that previous generations could have never imagined.

When we combine the technological advances of our day with the creative imagination of the modern architect, we come across an incredible advance in design, and CAD/CAM comes together with such a way of thinking. Architectural design may be conceived as an activity distinct from that of making, however when CAD/CAM-based processes are in concern, the boundary between representation and direct instruction for fabrication or for making blurs[2], as the data derived from architectural design work or from the architectural model become the direct data for fabrication.

[2] SCHODEK, Daniel; BECHTHOLD, Martin; GRIGGS, Kimo; KAO, Kenneth Martin and STEINBERG, Marco. *Digital Design and Manufacturing: CAD/CAM Applications in Architecture and Design.* John Wiley & Sons, INC. 2005.

6.2 Remarks on the Production Process through the Experiment within Architectural Concepts of Design and Production

The case study within this thesis was carried out in order to experience the process that CAD/CAM puts forward. The ease and difficulties encountered during the study showed the availabilities and requirements of the system, not only for a single object-torus, but also for any other possible application. It is seen that new technology comes with new demands. During the study it was discovered that the drafting environments generally used by architects supported CAD but not CAM, despite the availability of design development environments that supported both operations; which is an issue that clearly needs to be addressed.

The architect, using digital tools of modeling, needs to learn how to handle the architectural model, thus the architectural design, as a basis for manufacturing together with other aspects of an architectural project. The 3D model, apart from being the representation of the design, has evolved to become the design process. The architectural model has taken its place at the centre of design offering a collaborative design environment for all the actors involved in the building process. Architectural design is no longer a phase completed in the initial steps of a project life-cycle but has the potential to be a continuous and evolving aspect throughout the building process that can be manipulated by all the design actors.

As in the case with other industries (aerospace, automotive or shipbuilding), the building industry can also adopt itself to the potentials of this technological progress. Being a part of such a process, the lead architect has the chance to handle the building project as a whole, not only for large structural elements but also for very small construction details.

In the cycle of development, CAD/CAM technology proposes a new design perceptive to the field of architecture. CAD allows the architect to manage the overall geometry of the building, and now, by utilizing CAD together with CAM, the architect has the opportunity to manage the overall process of building. The link that CAD/CAM technologies can serve between architectural design and construction/manufacturing/fabrication processes of building and the way to handle the collaboration among the parts has been tried to be demonstrated by the case study, which actually showed the entire process of CAD/CAM. However, it should never be forgotten that new technology comes with new demands, and the architect needs to be able to determine these demands and their requirements, and act accordingly in order to use all the potentials of the system.

6.3 Expectations – Future and Concluding Remarks

It can be said that the future will bring new potentials. High capabilities in information exchange and information technologies shorten the distance between the designer and the engineer. Time is much more expensive now than it ever was in the past, and today's architect does not have the benefit of the hundreds of years that Antoni Gaudi once had.

Throughout this research and the case study, it has been observed how architectural design can benefit from the opportunities provided by CAD/CAM and the technologies behind it. The Bilbao Guggenheim Museum of Frank Gehry is maybe the most striking example in this respect. Although there are many aspects of digital tools that the architect needs to learn, the potentials they bring to architecture cannot be denied. As Charles Babbage once said: "(The Difference Engine shows) the degree of assistance which mathematical science is capable of receiving from mechanism"[3], the examples available to us show the degree of assistance which architecture is capable of receiving from technology.

[3] BABBAGE, Charles. "On the Mathematical Powers of the Calculating Machine" 1837 in: *The Origins of Digital Computers Selected Papers,* (p. 17-52) ed. Brian Randell. Springer-Verlag Berlin-Heiderberg, 1973. (p. 17)

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