File to Factory Technology;

Architecture and Architectural Values

By

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This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Hereby I would like to express my deepest gratitude for the inspirational and continuous support from my supervisor Dr. Michael Grant who has guided me throughout the course of this research.

The finished document is dedicated to my dear parents who patiently offered their unconditional and heart warming love which has encouraged me in every stage of my life.

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Abstract

This thesis examines the past, present and future of industrialised architecture and roles of computing in the evolution of the practice of architecture. Modern manufacturing industries are now fully integrated with computers which control the management, processes and manufacturing of products offering increased levels of sophistication and quality while delivering enhanced economies and efficiencies. In this respect architecture and the construction industry have not kept pace with the advances demonstrated in other industry sectors.

Given recent progress in the realm of digital architecture, the hypothesis is that the potential industrialization of architecture and the greater use of machines to make buildings do not necessarily result in a higher level of undesirable standardization but might lead to a similar revolution as seen in the wider manufacturing sector. This premise

is initiated by considering buildings as the result of a production processes, a view much closer to the field of product design.

The methodology underpinning the research has been to follow the evolution of the design process and the introduction of design computing through the development of increasingly sophisticated technologies commonly employed within a range of industries. Within this progression it will be shown that all aspects of computing now facilitate the advanced levels of design, communication, planning, manufacturing and construction of just about all modern products. While it is acknowledge that architecture has a different market from most other manufactured goods it will be evident that there are aspects of new manufacturing technology that if adopted, would have fundamental implications for the construction industry.

Within the context of a broader investigation exemplary projects have been chosen to illustrate some of the desirable qualities of leveraging new technology. These will demonstrate that architectural quality can be enhanced, efficiency and economy can be delivered and that mass customisation can be achieved in a more sustainable and advanced level compared to other conventional methods.

1. Introduction

The research reported here intends to investigate new possibilities for building design and construction through the application of the emerging digital technologies. Given recent advances in the realm of digital architecture, the hypothesis is that the industrialization of architecture and the use of machines to make buildings should not necessarily result in a higher level of standardization or just the repetition of forms and spaces which had become familiar in the era of post war mass produced buildings. This document seeks to explore examples demonstrating different approaches in applying digital technologies to the making of buildings where the research has identified exemplars of the ability to enhance creativity, increase efficiency, improve environmental impacts and tailor outcomes through individual customisation.

Usually the introduction of new technology or working methods will be viewed as a threat to traditional values but here it is possible to propose a synergy from within the examples cited above that would serve to enhance and protect the existing vernacular values of traditional architecture.

Finally, there is the prospect that new manufacturing techniques and machinery could pave the way for the development of structures which could provide greater scope for the design and customization of living spaces based on the needs of any individual while also delivering economy and efficiency within a sustainable product lifecycle.

1.1. Motivation and problem statement

For ordinary people, the question of 'how are complicated building forms created?' was simply answered by the response 'using computers' and nothing more. Basically the designs which were being developed by pioneering architects such as Gehry, Foster, and others. were not common practice amongst the majority of other architects; therefore for a while people could see buildings which not many

knew the details of their design and construction. On the other hand, conventionally most of the use of computers in architects' works is dedicated to the creation of models which only carried a representation of the geometry but could not be attributed with the real life features of buildings; consequently this is the only aspect of Computer Aided Design known by many people and even architects. These types of models were not useful in simulation, evaluation and ultimately the manufacturing of the design. With the presence of Computer-Aided Design applications and techniques as design tools and not solely as means to visualise illusions, designers are now able to add real life features to their designs and assess them in a virtual replica of the real world. They also could define some rules which can for example govern the structural features of design and keep it in the feasible margin(Kolarevic, 2005).

Looking at the cities and our living spaces, we realise that, in the real world of building construction the majority of our design proposals are based on conventional concrete and/or steel and/or timber beams and columns which, based on the nature of the materials and the conventional construction methods, are lacking the capability of handling complicated and multi curved forms. In the mainstream of the current trend in design and construction, apart from the limits in form generation, projects also inherited some complications on the construction site. In contrast with the historical vision of a Master Builder, architects were becoming more and more distanced from the construction work. Projects were largely designed by a person or a group and built by another group; usually the two groups had minimal knowledge about each other's work. As a result contractors and subcontractors faced problems that were not resolved during the initial design phase and the final structure was subject to numerous alternations, distancing them from the original design. The lack of transparent communication between all groups is wasteful and expensive and in some cases may cause the dilution of important design concepts in the final product. Even if the design and construction teams were fully integrated and share a good understanding of each other's work, the conventional construction methods seem to be incapable of realizing complicated designs and taking advantage of new materials. With the expected standards in aesthetics and quality, producers need new tools, techniques and means of communication in order to update their workflow and products (McMahon & Browne, 1998).

The built environment forms a large part of the cultural identity of many countries which in turn means that architecture, as a cultural phenomenon, is influential on the culture of people and therefore the local culture is consequently influential on the architecture of that region. In fact architecture and local cultures share numerous similar roots such as climate, historical background, religious beliefs, and local customs. Nonetheless technical changes in the way of delivering buildings have always had an influence on this cultural link. History has shown that the growth of the global population had increased to the extent that the material needs of society can no longer be met by hand crafted artefacts. The root of this problem lay in the limitations to the quantities of goods able to be produced by manual methods and the attendant lack of economy in manufacturing both in terms of the time scale and the material usage involved. In response to this scenario, industrialised processes evolved to mass produce basic items in such quantities and at a cost point that was attractive to the consumer market. As a consequence processes and components became increasingly standardised which, while delivering the desired efficiencies and economies, have also reduced consumer choice and the opportunity for local optimisation.

The significance of increased levels of standardisation is also evident in some aspects of the design and construction of our built environment. At its extreme extent this has resulted in generic building types being constructed all around the world with the consequence that there is an over reliance on electrical and mechanical services to tackle the problem of poor indoor environmental quality. There is a similar risk in ignoring local geographical and cultural features which tend to result in incongruous and unsuitable architecture.

After the Second World War, the process of modern architecture [modern architecture has varied description and scope and is primarily based upon the industrial revolution of mid eighteen century. The term is widely used to describe the architectural movement at the beginning of the 20th century.] was subject to a major transformation that not only resulted in the evolution of modern architecture in western countries but also had a significant influence on the architecture of other countries. The extent of the destruction left by the war and subsequent socioeconomic necessities of reconstruction brought modern architecture and urbanism into consideration more than at any other time in history. 'More', 'Cheaper' and 'Faster' were three fundamental trends that the societies of post war Europe were seeking to follow in the reconstruction and revival of their war-torn cities (Etesam, 1995). Accordingly, high levels of standardization appeared to be the favoured solution in the process of construction and renovation of the buildings and cities. Hence, due to time and cost shortages, application of previous forms, structures and construction techniques were often abandoned and architectural decorations and details were sometimes excluded in order to achieve a higher rate of productivity and efficiency in building construction. This approach to the creation of new buildings and the revival of cities has become even more intensified after the Second World War (Mohammadzade, 2009).

The influence of post war shortages in Europe had generated a style of buildings and urban construction which has been replacing the local architecture in developing countries [especially where they were technologically dependent on Europe and the United States]. Nevertheless the penetration of this relatively new style has mostly ignored any sort of domestication that reflects the local social, economic, cultural, climatic traditions and identities (Mohammadzade, 2009). Although there might be some adaptation to methods, structures, forms and the resulting spaces, the majority of these revisions are now regarded as shallow and not fully compatible with, and practical for, peoples' daily lives. The assumption here is that what is formed as modern architecture in developing countries appears to be mostly deprived of any local identity, products that affect their users in every possible way but still not responsive to their needs in respect of climatic, and cultural/social considerations. Therefore, the incompatibility of architecture with the local necessities has resulted in an increasing use of energy and natural resource, causing modern buildings and cities to become increasingly unsustainable both socially and environmentally.

Nowadays there is a better awareness of the limitations and problems of mass production in building construction. People recognise that the quality of living spaces relates to individual lifestyles and individual needs, many of which are informed by cultural and social differences among diverse populations. Every day we hear about new methods and devices which can reverse the negative effects of global standardization, but their influence in the building design and construction industry and the impacts of new possibilities in the realm of the built environment are as yet unclear. What is the future direction of construction and Architecture? What percentage of the population is actually involved in the design and construction of habitable space? How can we increase the number of customized living spaces while improving the economy of construction projects? How can we design and build more efficient and creative architectural products.

1.2. Research aim and objectives

The aims and objectives which this research seeks to address are as follows:

- **One:** To investigate and describe the state of the art in the realm of Computer-Aided Design, Computer-Aided Manufacturing, process planning and the organization of work in digitally integrated production industries and to study the possible potentials for improvement of the workflow and production.

- To consider the history of digital design and production in order to identify emerging trends
- To investigate the role of computers in the systematic approach to the design and production ○ To compare the results of applying conventional and digital tools
- To demonstrate different aspects of the application of digital technology
- To determine the advancement in the quality of products using computers
- To illuminate the design/manufacturing link in a modern organization ○ To investigate new means of project planning using computers ○ To explore new potentials for supplier/producer/customer linkages through the digital environment
- To outline the potential for ultimate productivity and efficiency through new systems, methods and devices
- To identify new strategic trends in design and production ○ To define the new approach towards making comprehensive models of products to be used in design, production, product lifecycle and recycling procedures

• **Two:** To study the notion of conventional approaches to industrialized architecture and also to investigate the role of CAD and CAM in its progress.

- To investigate the history of industrialized architecture and to follow its path of progress, reasons for failures, elements of successes and changes in the flow of progress
- To define the poplar methods which are currently used to construct prefabricated buildings in order to investigate each method’s advantages and disadvantages.

  - To exhibit examples of using digital technologies for gaining extreme creativity, productivity, efficiency and customization in designing and making of buildings. In fact to demonstrate different aspects of digital architecture.
- **Three:** To determine the role of digital architecture and to explain the potential for new improvements in this field.
  - To study the impacts of globalization and undesirable standardization within local societies
  - To highlight the loss of vernacular values and subsequent building failures
  - To investigate new systematic and technical improvements with the potential to reverse the negative trend
  - To establish the strategies to democratize architecture through making architecture and uniquely designed spaces available and affordable for the majority and to explore the potential for involving communities in the creation of their living space.

1.3. Methodology

Based on the objectives of this research, the sequence of work was designed to synthesise the literature and provide an original interpretation of the collected information. The aim is to build a narrative that connects the rise of computing and its role in the delivery of economies and efficiencies within modern manufacturing. Also to describe how aspects of technological and economic progress have influenced the global construction industry. Further development of the concept will be dependent on knowledge concerning the current qualities of the digital design and production area, an understanding of the differences compared to traditional methods and will conclude with observations on the future directions in the field.

Literature based studies will provide more specific data regarding the history of industrial manufacturing of architectural products throughout recent history as well as investigating the available common practices in this field.

Studying the architecture in the northern and central regions of Iran lays out a historical context and will establish the fact that industrialization and modernization have been culturally and ecologically influential within the local communities. The intention of this part is to demonstrate the necessity for changes in the ways we design and build our living spaces.

The next stage of research includes reference to examples in order to illustrate how different influences have impacted on architectural design in different periods of time. The intention is that this part of the research will use existing buildings as examples to show how digital architecture can influence the design and production of building.

The presented research consists of a few main topics, each playing an essential role in the formation of the narrative of the written document. One of the key elements of this research is CADCAM and the quality of work in such a system of design and production. In order to establish a firm knowledge base in this topic the research refers to sources such as: *CADCAM Principles, Practice and Manufacturing Management* by Chris McMahon and Jimmie Browne (McMahon & Browne, 1998); Digital design and manufacturing by Daniel Schodek (Schodek & Bechthold, 2005); *Green BIM* by Eddy Krygiel (Krygiel & Nies, 2008).

As the other major field in this research, literature based research then targeted the industrialisation of architecture. The main references reviewed are: *Architecture, Technology and Process* by Chris Abel (Abel, 2007); *Managing the building design process* by Gavin Tunstall (Tunstall, 2006); *Architecture in the digital age, Design and manufacturing* by Branko Kolarevic (Kolarevic, 2005); *Refabricating architecture* by Stephen Kieran (Kieran & Timberlake, 2004); *Modern architecture* by Kenneth Frampton (Frampton, 2007); *Prefab architecture* by Ryan Smith (Smith, 2010). In order to discuss the main topics in detail and explore the most recent works, developments, innovations and case studies in the realm of digital design and manufacturing, websites [Such as the 'Broad company' website and 'Facit homes' website etc.], published papers, governmental and institutional reports, interviews and books such as *Digital Gehry* by Bruce Lindsay (Lindsay, 2001); *Symphony: Frank Gehry's Walt Disney concert hall* by Deborah Borda (Borda, 2003); has provided some very useful material.

As an objective, this research intends to highlight the potentials of CADCAM technologies for making radical changes in the architectural process and architectural products. In fact to introduce what has been achieved and what could be achieved by using the Digital techniques in order to preserve architectural values [creativity, innovation, efficiency, productivity, practicality, customisation, availability] and how the built environment related problems of our societies could be resolved by these novel methods and devices. This is gained through reviewing the most recent presentations in well-known conferences [e.g. TED] and ground breaking projects that are being developed by leading academic organizations or small groups and individuals.

1.4. Chapter plan

The two chapters, which form the main body of this research, can be described briefly as follows:

Chapter two: Computer-Aided Design and Computer-Aided Manufacturing technological overview

This chapter consists of twelve subchapters which intend to demonstrate the technical capabilities of CAD and CAM. The initial part [2.1] is a brief exploration of the diversity, penetration and capabilities of CAD. Of particular note is how systems were introduced by the high value, heavily capitalized industries but quickly became more widely available to the general industry. In parallel to the advances and adoption of CAD it can be seen that there is also a growing advance in associated CAM technology.

After discussing the recent history of CAD CAM systems the next part [2.2] seeks to review the typical definition of a design process by mapping a path through some well established models of design. The intent is to provide the context for a more in depth discussion of the relationship between the design process and the technology of the production line.

Chapter 2.3 is an introduction to the concept of geometrical representation which starts by briefly defining the idea of 2D representation followed by a discussion of representation through the adaption of graphical standards which reflects on the deficiencies and limitation of the process. By the introduction of 3D models more intelligence could be incorporated in the model.

Innovation within CAD triggers a movement from representation models towards a system which can facilitate design evaluation and other design related processes. In section 2.4 it can be seen that differing types of models could be made using computers and what useful kinds of data could be attributed to them and how these models can help throughout the design process.

As outlined in chapter 2.5 we are faced by the new found abilities of digital techniques which can potentially revolutionize the conventional ways in which we manage the organisation of projects. Based on the materials presented in previous chapters, the discussion so far has revealed that computer aided design has become ubiquitous and the development of design tools has led to the ability to construct, simulate and evaluate a representation of reality and so the next challenge is to provide tools and techniques that also provide design decision support.

Despite the fact that what was mentioned so far was mostly focused on the design phase the research reported in chapter 2.6 demonstrates that in a concurrent systems of work the definition of the relationship between design and manufacturing is not just limited to discrete and sequential tasks but can be considered as a unified and simultaneous process. The aim is to identify strategies which can lead to increased efficiency and economy and also provide the designer with better oversight and control of the production process.

Having introduced the fundamental concepts of computing in design, process planning and manufacturing process it is essential to introduce developments in machines and machining processes. In chapter 2.7 it can be seen that as the technology has developed we have witnessed the introduction of a wider range of supporting computer based tools i.e. automatic programming tools and cutter location data files. The technology has also been extended throughout the production line and now supports rapid prototyping and robotic controls.

Section 2.8 looks at different aspects of manufacturing planning by initially investigating discrete manufacturing and the contrast with continuous manufacturing and ultimately the effect of industry's organisational changes to meet the challenges of customised, customer driven manufacturing. The case is made such that the manufacturing process is all about an understanding of the customers' desires and the ability to convert data into objects. Planning this process is crucially integrated with time, cost and availability of raw materials.

The pursuit of ever greater production goals has led to the concept of Just In Time engineering JIT. In chapter 2.9 we will see that this system seeks to provide the 'right items' of the 'right quality' at the 'right place' and the 'right time'. This system considers the totality of the project and although hard to deliver may promise the greatest return. Key to this concept is communications, flexibility in machinery deployment, optimal accuracy and zero errors. Implementation of all the previously discussed computer based processes is essential to underpin the success of the system.

The impact of all aspects of the digital technologies on manufacturing has been compared to the industrial revolution of the previous century. Digital technologies are supporting all aspects of society and this impact is augmented by the ability of disparate technologies to communicate and reinforce each other e.g. autonomous vehicles. Section 2.10 is intended to briefly demonstrate the latest trends in the progression of CADCAM technology. As manufacturing and fabrication become more complex there are more teams working on a greater variety of aspects of the project. This calls for closer collaboration and better communications. On the other hand the logical extension of CAD systems has resulted in the development of a product model that contains all the information relevant to that object. Networks and internet communications facilitate the sharing of knowledge and facilitate the connection of those people who may work on the same project whether located in the same group or from different groups. Nowadays accessing knowledge and updating the central data model is a key to the success of projects where collaborative virtual teams may gather from different parts of the world and participate in projects, miles away from their own location.

Since the focus of this thesis is the architecture industry, chapter 2.11 introduces the Building Information Models as one family of product model that is used in building construction. Traditionally production of the necessary data to transit a project from the design phase to the construction site was done manually as a result of the collaboration of different groups of experts, each controlling a different discipline. When computers stepped in the realm of building construction, activities such as 2D drafting, structural estimation, bills of materials production and project management scheduling were performed more easily, faster and with greater precision. The ultimate goal in this field appeared to be the creation of an integrated organization to contain all the building related activities in one virtual place which can provide better communication between different stakeholders.

Section 2.12 provides a summary of chapter 2.

Chapter three: Industrialised architecture and the contribution of CADCAM

In the previous chapter some of the features of CAD CAM systems and the ways in which they can be used to improve the workflow in various industries have been described. It can be a good time to narrow down the discussion to the industry of interest which is Architecture and Building Construction. The intent of the first part of the third chapter [Traditional approaches towards industrialised architecture] is to go back into the history of 'prefab' buildings; to the time when there was no sign of computers or NC and CNC devices. Although the main requirement of this chapter is to introduce the history of construction systems which would ultimately lead to the arrival of 'File to Factory' methodology however, the narrative of this chapter ends right before the time when computers get involved in the construction industry since the application of the digitally-driven methods are going to be discussed in following chapters.

Following the exploration through the history of prefabrication, chapter 3.2 attempts to study the various types of popular materials used in prefabricated construction and the different conventional prefabrication approaches and industrial techniques that are being used to apply them in buildings. Apart from the introduction of different categories of building elements that are being used in such buildings, different materials and methods of using them to fabricate those elements are briefly explained.

As was mentioned towards the beginning of this document, any systematic or technological modification of the process may have vast cultural impacts both on the local societies where buildings are built and in the groups which participate in projects. The intent of chapter 3.3 is to demonstrate the depth of these cultural changes and the potential of these systems to create a new path in the progress of architecture and construction that can lead the industry to deliver a more suitable built environment both from a cultural and environmental perspective. Hereby the first part of chapter 3 is concluded by studying the history of prefabrication, conventional prefabrication methods and an example showing the impacts of current global standardisation on local societies.

The second part of chapter three illustrates three examples each showing a distinctive approach in the use of CAD CAM techniques. The first example is dedicated to a discussion of the creative approach of Frank Gehry in designing the

Disney Concert Hall in Los Angeles. Equally there is mention of many other inspirational projects from all around the world which used digital technology to take the definition of building aesthetics and form generation to a higher level. The second case describes the Broad Company's pursuit of efficiency in the design and production of multi storey buildings. The efficiency savings run all the way through the building lifecycle and even impact on recycling and reuse. Their level of efficiency in design, evaluation and construction methods have broken many world records and they are still working to improve them. The last example of this document as shown in chapter 3.6 defines the work of a relatively new group called Facit Homes. Their approach to the use of CAD CAM is to take building construction projects extremely close to the Just In Time concept. Trying to apply as many as possible of the optimization techniques in their production process, keeping the process as simple and affordable as possible, creating a flexible production line to reduce the manufacturing time and associated cost as well as focusing on product customization have made their approach to CAD CAM very interesting. The result is highly customised buildings which have been constructed using modern techniques and machinery that could now be more readily available for wider application. An improvement that could not be anticipated only a few years ago.

Based on the information presented throughout the preceding chapters we are at a point where outcomes and results of the use of digital design and manufacturing in the realm of building architecture could be identified. On the other hand in chapter 3.7 the focus is to show the most recent improvements of digital fabrication systems which can be accessible for the majority of people even in remote areas of the world. This time, globalization does not necessarily means that people need to use the exact same products all around the world. Using these newly available methods and devices can enable us to produce almost everything on a global standard but highly customized based on local needs and the availability of resources.

Section 3.8 presents a brief summary of chapter three. In this section the reasons why such examples have been chosen through the course of this research and the relationship between these examples have also been explained.

2. CAD and CAM technological overview

Before getting involved in any kind of project and starting any design work or production initialization or even planning the projects' progress, whenever there is the prospect of using any type of methods or strategies it is an advantage to know about the abilities, limits and the quality of their current contribution in other projects. This way the direction of projects in which different project teams may get involved is clear and it becomes possible to avoid many of the difficulties that may occur later in the process. It is clear that the philosophy of the existence of engineering and teams of engineers with different skills in every project have been based on the optimization of processes, materials used and also the organization of the work force and project framework etc.; however the limits and demands of the modern market and features of the modern industries do not allow much in the way of trial and error or defects in the manufacturing of products as may have existed a few decades ago. The current experience of providing services and artefacts for society establishes the demand for high quality delivered in a short period of time to a large number of users with as little as possible waste and desirably with zero defects. Growing competition and technological innovations have raised the bar in the case of expectations in all aspects but fortunately computer aided systems have brought new resources and solutions to the work of designers, engineers and manufacturers. Based on what is said so far and in order to realize the quality of the contribution of the digital technologies in production industries, the contents of the twelve sections in chapter two is intended to investigate the design approaches and tools. This is then followed by an introduction to manufacturing devices, organizations and planning strategies. This then leads us towards the ability to envisage the generation of new forms, flexible production lines, mass production and customization all gathered together in order to facilitate the realization of design proposals and raise the quality of products and optimize the processes, material use and human resources.

Part one: History and basics

2.1. CAD and CAM progress timeline

2.1.1. Introduction

This chapter intends to deliver a very brief narrative in regard to the developmental chronology of Computer Aided Design [CAD] and Computer Aided Manufacturing [CAM]. For the purpose of commencing an investigation on any matter it is always useful to step in through their background to gather knowledge about the way which led them to the current point of existence. Studying the history of 'CAD' and 'CAM' which are indeed the core concepts of the 'File to Factory Technology' can be regarded as the foundation from which it is possible to enter the vast realm of digital technologies being used in the design and manufacture of all products, and in the case of this research, buildings. CAD can be seen as the starting point for the digital production process; therefore the historical research within this document will begin with Computer Aided Design.

2.1.2. CAD

Even a cursory review of the work of most modern design companies over a wide range of industry sectors establishes the fact that using CAD has become an inseparable element in modern design and manufacturing. It is not only technically advanced industries such as aerospace, architecture and medicine but it has also penetrated through domains such as entertainment, advertising and other creative industries as exemplified by film and animations, one example of which is shown in Figure 2 .1. Originally developed in the early 1980s as an aid to drafting and documentation, software now plays a more dramatic role in its ability to expand the capabilities of designers and now may be utilised to demonstrate, calculate, simulate, evaluate and fabricate their increasingly highly detailed products. Basically CAD is the foundation for modernized systems which allow better communication and the exponential growth of creativity and productivity in almost any project in any domain (McMahon & Browne, 1998).

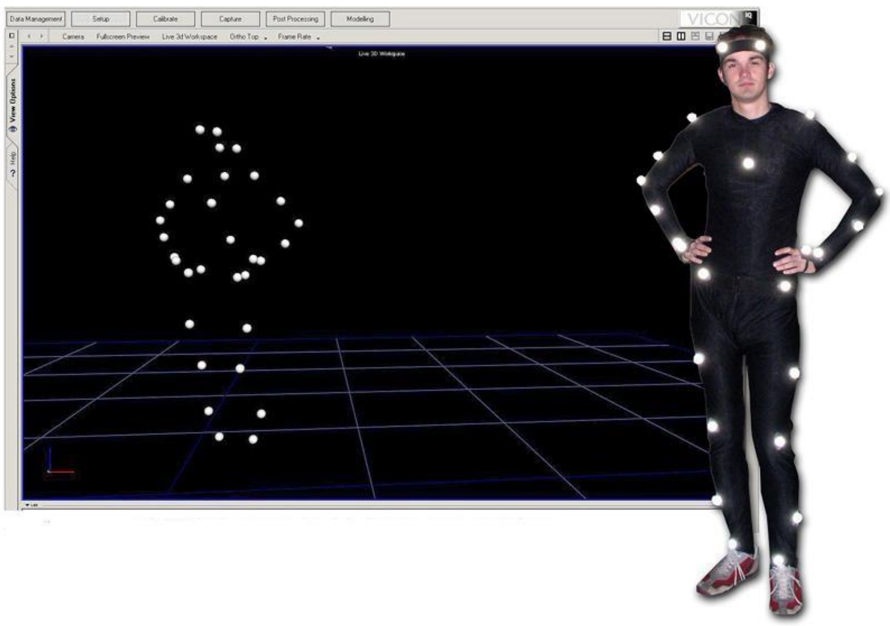


Figure 2 .1 Motion capture

'Motion capture', a digital technique used in animation and movie making to recreate natural movements in digital formats. Basically a variety of sensors will be located on a person's body [especially on the place of the body joints]. Those sensors capture the movements of each join and body parts. These data then could be used to make digital movie frames or even to move robots in factories. Picture (Hamm, 2007).

Previously the expectation of the output from CAD packages was limited to 2D printed sheets or virtual models. Now new and advanced rapid prototyping techniques have the ability to produce a physical prototype of the design relatively easily and in a considerably shorter period of time as compared to traditional techniques [Figure 2 .2]. Unlike before, CAD models in a more sophisticated BIM system [an object-oriented system] now contain more sophisticated data [such as bills of materials, schedule, performance data, production plans, etc.] rather than just the classic package of shapes or dimensions [known as graphic representation]. By the presence of these relatively new tools the traditional manual methods of drawing and presentation are being gradually eliminated even in many universities and schools. Since the development of CAD systems are highly related to computers, knowing about computers can take us to the roots of this relationship and emergence of CAD (Krygiel & Nies, 2008).

Figure 2 .2 Stereo lithography
Stereo lithography, a rapid prototyping technique using information from 3D digital CAD models and produces the physical replicas by plastic materials. Picture (Proto3000, 2012)

A history of devices which can be considered to be computers [based on the definition of computers as machines capable of calculation and programmability] dates back to 2500 B.C. when Sumerians used the Abacus (Ifrah, 2007); but in fact the first time when the term Computer was used can be traced back to the early 17th century (Oxford English Dictionary, 2009). Nonetheless mankind had to wait until the mid 20th century when Konrad Zuse [Figure 2 .3] developed the concept of the first digital and programmable computers as the initiators of the current theme in the digital technologies (Flippo, 2013). In 1940's, at the time when the development of electronic science in the realm of computers was happening, Robert Isaac Newton's Study on the mathematical definition of curves founded new descriptions of geometry that have opened new possibilities in the formation of digitally-processed geometries and added the promise of graphical processing capabilities to computers that previously were mostly used for calculations

(Inspiration feed, 2012). Almost a decade later the term 'CAD' was first used by Douglas T. Ross who was inspired by the display devices on American defence radar systems that can now be considered as the first graphic systems and were in use from 1950 (Ross, 1960).

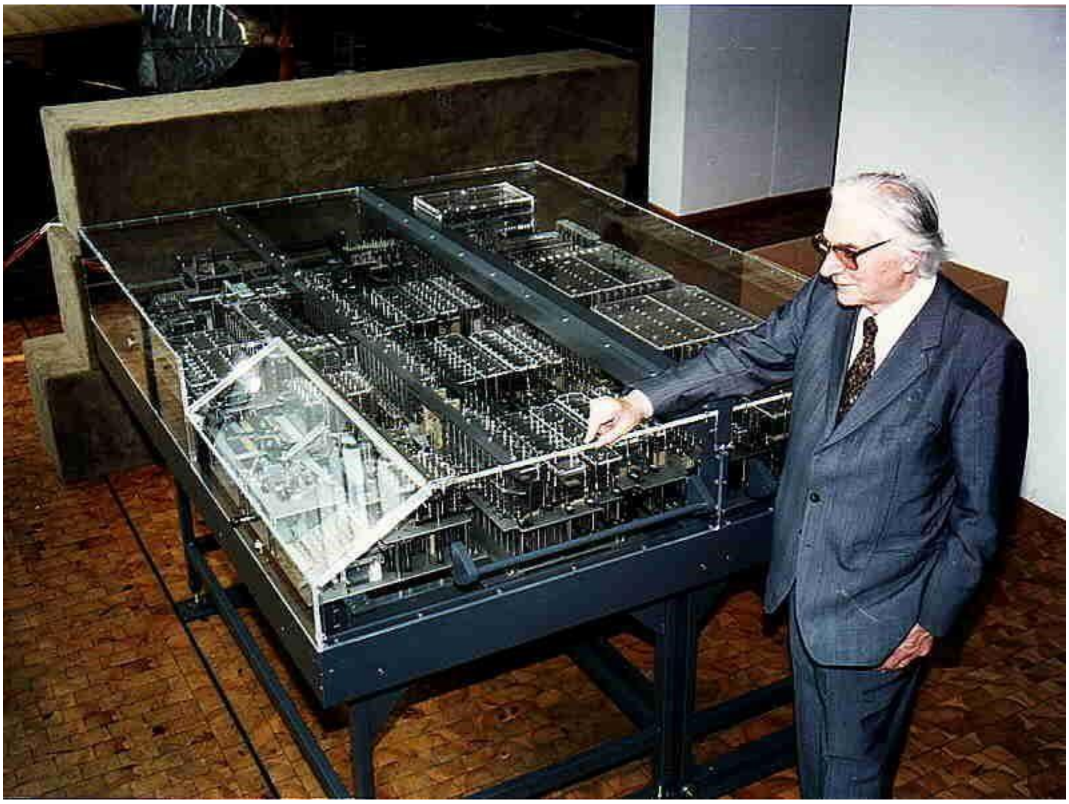


Figure 2 .3 Konrad Zuse and the Z1
Konrad Zuse beside his masterpiece, 'Z1' the first programmable digital device. Picture (Staatskanzlei, 2010).

It is evident that the aerospace and automotive industries were at the forefront of development and were able to take full advantage of digital graphic systems. European and American car manufacturers focused on design, calculation and production of multi curved surfaces for their products and among them Pierre Bezier has been recognised as developing the most distinct inspiring and pioneering work in designing car bodies at the Renault. In 1957 Dr. Patrick Hanratty later known as 'the Father of CAD/CAM' programmed the 'Pronto' the first of a generation of CNC systems. Later in the early 70s he explored the limits of Computer aided technologies by founding the 'Manufacturing and Consulting Services Inc.' followed by the production of the 'ANVIL' CNC packages [Figure 2 .4]. His company developed software and hardware bundles which were used at that time by leading companies such as McDonnell Douglas. Even though there have been numerous advancements in the area of CAD/CAM technologies, it has been estimated that 70% of all the current CAD/CAM systems are based on what the Manufacturing and Consulting Services' presented as their core system (MCS, 2012).

Figure 2 .4 Hanratty and the Anvil-4000

Dr. Patrick Hanratty beside the CNC package called ANVIL-4000 which was released in 1981 by his company MCS. Picture (Dalton, 2004)

The progress in digital geometry is related to the advancement in computers' hardware and software, but the initial breakthrough can be attributed to the sketchpad project [1960] by Ivan Sutherland at the Massachusetts Institute of Technology [Figure 2 .5] which facilitated a better user interface with computers. In fact the sketchpad was the first tool to develop graphical interaction and was followed by innovations such as the digitizer and the light pen (Sutherland, 2012).

By the end of the 1970s what was at hand as a CAD system at a cost of $125,000 consisted of a 16-bit minicomputer with 512kb of ram and storage capacity of up to 300 Mb (NASA). Due to the high cost of the hardware, CAD technology first became used in those industries with a particular interest in form generation and geometry simulation such as within the car, aerospace and electronics domains but gradually the technologies achieved penetration within a wider range of industrial areas.

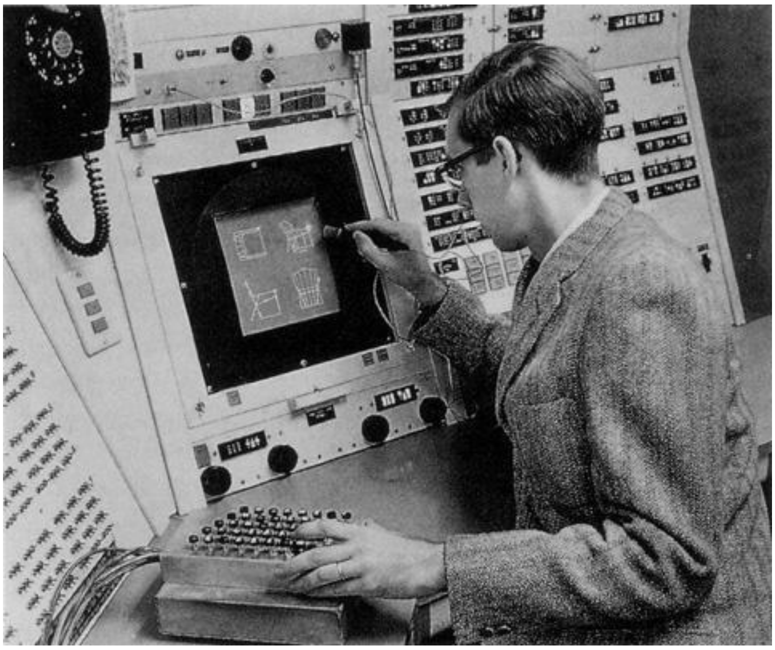


Figure 2 .5 The Sketchpad
Ivan Sutherland's Sketchpad console, 1962. Sketchpad is operated with a light pen and a command button box [under left hand]. The four black knobs below the screen control position and scale of the picture. Picture and descriptions (Müller, 2012).

Time has made all those new technologies not to be seen just as exclusive products and now many other companies and industries find these technologies affordable and are able to leverage their capabilities in all areas of design and manufacture. In the mid 60s the first interactive graphics manufacturing system was designed by Hanratty in collaboration with the General Motors and was called the 'Design Automated by Computer'. In 1962 the Man-Mac device had been developed, focusing on designing interior office spaces. Eight years later, the narrow path of CAD technology became wider as many companies focused their work so as to offer further advancements in mechanized design systems. This expansion is mostly owed to the work of Dr. Hanratty and his company 'MCS'. In 1972 'ADAM' [Automated Drafting and Machining] was released by MCS and soon found its place among the pioneering commercial digital products serving mechanical design. At the same time the first prospect of an extension of CAD towards integration with CAM has been made possible due to innovation of 3-axis N/C machining tools (MCS, 2012).

In mid 70s 'AMD' [Avions Marcel Dassault] an Aircraft manufacturer acquired software licenses [a package called Computer-Augmented Drafting and Manufacturing also known as CADAM] from Lockheed. In just two years [1977] they formed a group focusing on creation of 3dimensional interactive software which was the predecessor of CATIA [Figure 2 .6] [Computer-Aided Three-Dimensional Interactive Application]. The first version of CATIA was released in 1982 as an addon. It was capable of 3D design, surface definition and numerical control planning (Bernard, 2003).

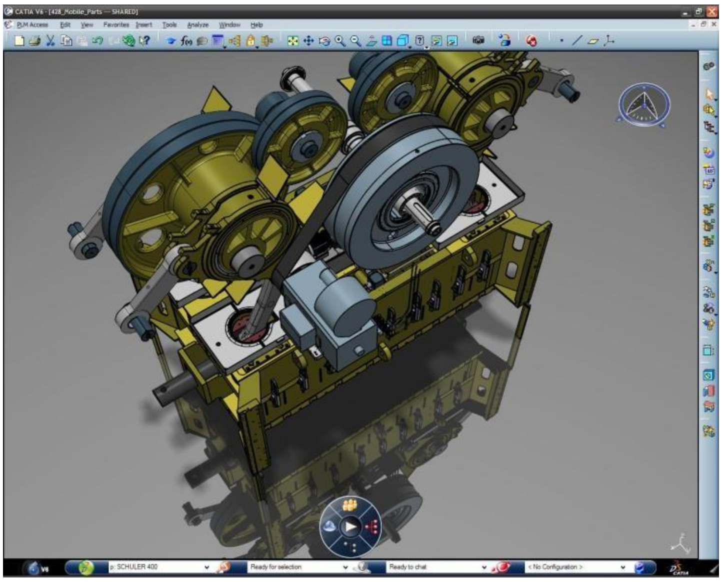


Figure 2 .6 CATIA
A screenshot showing a recent version of the CATIA work environment designed for mechanical engineering projects. Picture (Idex Solutions Inc., 2004).

That breakthrough coincided with the advent of more powerful computers at lower prices and the formation of the 'Autodesk' Company. Autodesk aimed to develop

CAD software for PCs with the goal of marketing at a relatively low price [under $1000] and the outcome was 'AutoCAD' [Figure 2 .7]. Continual development and the constant improvement of tools and abilities made this CAD software arguably the most popular amongst the current users of the technology. However other companies such as Bentley systems [Est. 1985] also brought many of new tools and techniques into this world.

Comparing to other major industries, architecture was among the first to benefit from the efforts of software developers who produced a modelling application called 'ArcCAD', specific to Architectural uses, in 1991. In 1995 Autodesk became the fifth leading software company due to their outstanding improvements onto AutoCAD and 3D studio. Their attempt to produce specific version of CAD software for each field of industry proved to be a great success to the company. It was mainly their endeavours which made it possible for users to purchase comprehensive CAD software in a reasonable price and run it on their own ubiquitous PCs and make the best out of cutting-edge technologies, it was accessible and responsive to students, professionals and at the highest level of industrial needs. Their round-the-clock technical support and constant development cycle keeps Autodesk always a few steps ahead of their users and responsive to their needs (Jassi, 2013).

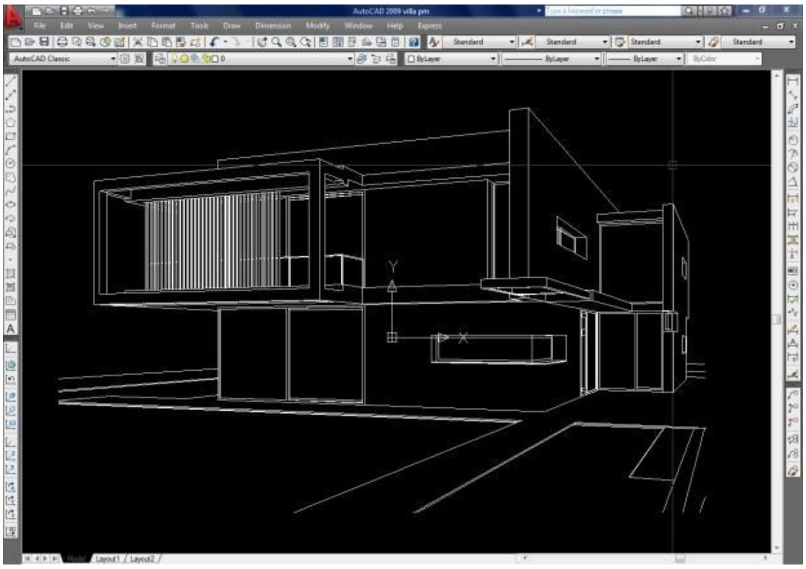


Figure 2 .7 AutoCAD
A screenshot showing a recent version of AutoCAD work environment. Picture (Cloud Atlas, 2013).

2.1.3. CAM

In general, the action which is defined by the term CAM or Computer Aided Manufacturing is to conduct the process of fabrication and provide necessary data to control machinery and manufacture a product through digitally driven devices and applications (Hosking, 1992). In a broader regard to the term it may also refer to other miscellaneous groups of activities controlled by computers which result in fabrication of a product which may range between designing to shipping schedules or supervision throughout the product process (Pichler & Diaz, 1992). The distinct product of CAM systems is a lean production process rather than just objects. It enables factories to produce in shorter periods of time with much less waste of material and energy. These elements have a direct influence on increasing productivity and reduction of production costs. Accurate machining tools develop the quality of final products. In addition CAM systems are capable of fabricating complicated objects which otherwise in most cases are not feasible using other conventional methods of manufacturing [Figure 2 .8]. A direct link between the designed object and the manufacturer in a CAD/CAM system also makes the final product as much as possible close to the purpose of the design and with as few as possible errors during the process (McMahon & Browne, 1998).

Figure 2 .8 Multi-curved surfaces
Curved steel plates in conference chamber of the DG Bank-Berlin designed by Gehry and Partners and built in 2000. Realization of some forms is not possible using traditional methods. Picture (Wikimedia-a, 2010).

What we see today as the great capabilities of the 'Computer-Aided Manufacturing' systems is originally stemming from 'NC' or 'Numerical Control'. Numerical control is series of programmed sequential commands which orchestrates one or more tools to execute certain pre-planned actions based on a precise timing and order of actions. These lists of commands are saved and fed to machines via various types of media. The concept of Numerical Control is also highly related but at the same time different from the mechanical control which existed long before NC. Examples of mechanical control could be found in car engines [camshaft], factory machinery or simply in 'musical boxes' [Figure 2 .9]. Their popularity can be traced back to the 1800s where cams mechanically controlled the movements of parts that each was capable of creating exact musical note by small pins or other family of components (Chapuis, 1980). Although cams had been used since 300 BC it was only around a century ago at the time of the Great War that those media which were responsible for dictating commands to machines had reached to their full potential and were used in many devices and war military machines(Wilson, 2002).

Figure 2 .9 Cam shaft

A cam shaft was designed to control the sequence of musical notes made by a metallic comb in old music box. Picture (deviantART).

Signalling the end for the dominance of mechanical control, John Parsons can be recognised as the father of NC machining tools(Ward, 1968). In the process of designing a helicopter his team used punched card calculators designed by 'IBM'. From this experience he formulated the idea to automate the process of milling, cutting and connecting the components and fundamentally initiated the automated manufacture of the aircraft. Thus the first NC manufacturing machines used punched cards [Figure 2 .10] to store and transfer fabrication and machining commands to the machines and acted as a connector of the design to the automated fabrication procedure(Smil, 2006).

Figure 2 .10 Punch card
Punch card operator, a person responsible for manually encoding the manufacturing commands and presenting them on punch cards. Picture (Fuller, 2010)

As the technology matured, the focus of research and development concentrated on bringing accuracy to automated processes. At this time the use of a Servomechanism was a step forward in the field of NC technology. Although engineers could transfer stored commands to machines the main obstacle in the way of increasing precision in production was the lack of machine feedback and an analytical unit in the production line which could assess the ongoing progress and redirect commands based on the production line conditions [basically to monitor and check to see if the process is going as planned, and that machines are doing the correct job and the results are as desired]. The presence of such control systems could also add to the operators' abilities to organize the machining process (Bedworth, et al., 1991). Parsons developed his machine and produced an integrated device to fabricate perfectly precise components which were a product of the work of the Servomechanism Laboratory at the Massachusetts Institute of Technology. Later in 1955 MIT replaced the punch card with a magnetic tape (Seames, 2002). NC techniques slowly but constantly spread throughout various industry sectors and the benefits were convincing to the point that Boeing published a report asserting the efficiency of NC (Makely, 2005). After further research on the input methods of the NC systems, MIT also published a report indicating the benefits of NC over manually controlled machines while criticizing the time consumption which had moved from fabrication of objects to programming the magnetic tapes. However the presence of computers was revolutionary and fundamentally changed the way things were being designed and produced.

By making the Whirlwind [real-time computer] at MIT in late 1950s [Figure 2 .12], John Runyon and his team dramatically lowered the time needed to produce tapes for NC machines by up to almost 97% through creating a program to automate the process which was seen to be much faster and more precise than the existing manual methods (Ross, 1978). The first computer integrated Numeric Control system was released as a result of MIT collaborating with the aligned group of aerospace companies in 1959(MIT Tech TV, 1959). In 1970 Lockheed acquired
'Digigraphics' [control data] and applied their technology to the fabrication of the C5 Galaxy [Figure 2 .11]. This aircraft has come to be regarded as the first integrated product of CAD/CNC.

Figure 2 .11 The C5 Galaxy
The C5 Galaxy, the first product of CAD/CNC technology. Picture (Demand Media, Inc., 2013)

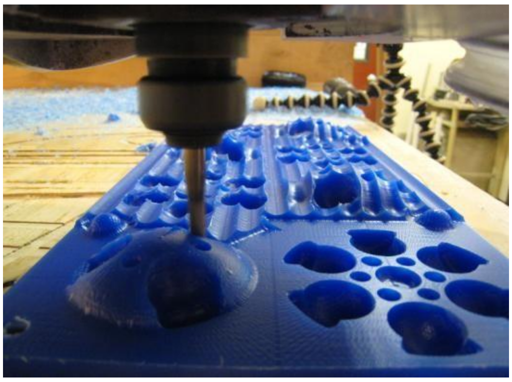
It is evident that changes in the field of CNC was not just the preserve of one institute or company and had been pieced together gradually to build the present state of the art. Despite all of the revolutionary innovations in the field of digital technologies, each of which had opened new opportunities for CNC to grow in capability and acceptance, in similar manner to that seen in the CAD world, it was the price reduction of the hardware and computer applications that made CNC popular amongst manufacturers. A large variety of industries has flourished under the capabilities of computer controlled production; nevertheless no one can disregard the contribution of both MIT and the Aerospace industries in helping promote the technology as being both affordable and practical. This developmental trend had continued until the present when it can be seen that there is consistent presence of CNC systems even in the smallest manufacturing companies.

Figure 2 .12 The Whirlwind Picture
(Ganapati, 2010).

As the technology began to deliver tangible benefits, more manufactures of this equipment brought more models to the market. This wider range of equipment also started to be used in a wider range of applications. This in turn meant that with this gradual acceptance there came a need for standardization of programming languages, fabrication commands and machine control. G-code is one such example which today has become a defacto standard (Smid, 2003).

Today there are all sorts of CNC systems each use series of strategies, applications and materials to serve a range of industries. Now there are 2D cutting and milling machines of a large variety of capabilities [Figure 2 .16], and other 3D subtractive [Figure 2 .14], additive [Figure 2 .13] and formative [Figure 2 .15] devices which add much more flexibility to production lines(McMahon & Browne, 1998). The current popularity of such system and with their affordability, ease of programming and the ability to integrate with almost all of the common CAD applications have brought these machines even to our homes. As well as seeking to develop extended capabilities of this technology, R+D engineers are also trying to reach a domestic market. This way, customers can buy a design, or even design something themselves [as CAD applications are getting as easy to be used by everyone], and ultimately print their own products that they might need in their homes. It may not be a legal or moral action, but one of the most recent examples has been the open source organization called 'Defence Distributed' who designed a rifle known as the 'Wiki weapon' which could be downloaded from the internet and could then be actualized by a 3D printer(Greenberg, 2012).

After briefly following the development of progress in the CAD and CAM technologies over the past decades in this chapter, the following sections of the CAD and CAM technological overview intends to deliver a more detailed definition of these technologies and to explore the capabilities they add to industries and their products within the current manufacturing domain.



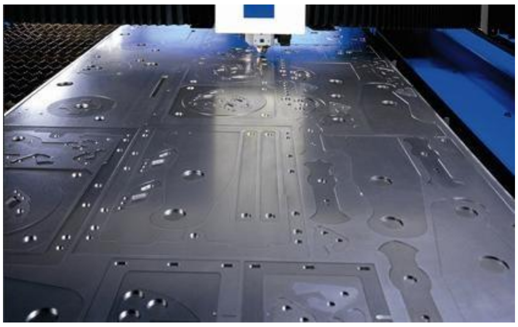


Figure 2 .16 Laser cut device
Laser cut devices are one of the 2D fabrication devices. The 2D operation can lead to the production of 3D objects as parts are assembled together. Picture (Subcon Laser Cutting Ltd, 2013).

Figure 2 .14 CNC milling
CNC milling machines are the min devices used for subtractive manufacturing. Picture (Lmnts).

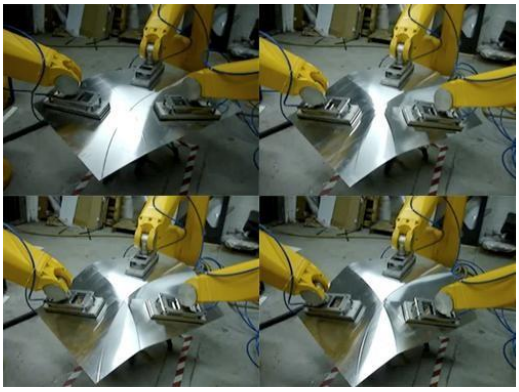


Figure 2 .15 Robofold

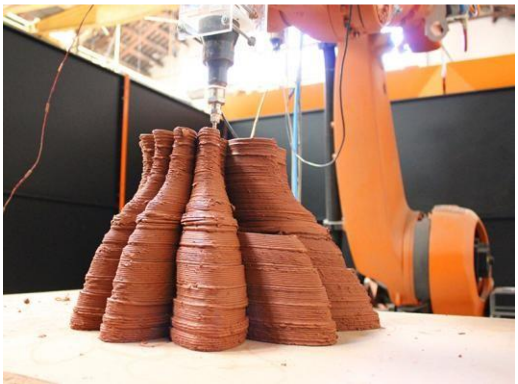


Figure 2 .13 Additive technique

RoboFold, a new formative CAM technology. Additive techniques use large variety of materials Picture (Piasecki, 2009). to create forms. Picture (designboom, 2012).

To summarise this section, figure below demonstrates the overall timeline of the CADCAM progression through the past seven decades. It contains significant movements which have happened during this period of time.

1950	The first graphic system was developed by US Air Force's SAGE (Semi Automatic Ground Environment) air defense system. The system was developed at Massachusetts Institute of Technology's Lincoln Laboratory.
1957	Dr. Patrick J. Hanratty known as "the Father of CADD/CAM" for his pioneering contributions to the field of computer-aided design and manufacturing, developed PRONTO, the first commercial numerical-control programming system.
1960	McDonnell Douglas Automation Company (McAuto) was founded. It played a major role on CAD developments with the introduction of CADD program.
1962	SLS Environectics in Chicago began development of the Man-Mac machine, intended to draft plans for interior office space.
1965	Donald Welbourn heard a lecture to the Engineering Society by Strachey of the Mathematical Laboratory (now the Department of Computer Science) on the early work at MIT on Computer Aided Design (CAD).
1967	Dr. Jason R Lemon founds SDRC in Cincinnati.
1972	The MCS company's first product, ADAM (Automated Drafting and Machining), was released in 1972, ran on 16-bit computers, and was one of the first commercially available mechanical design packages.

1975	• Electronic Data System Corporation (EDS) is founded. • Avions Marcel Dassault (AMD) purchased CADAM (Computer-Augmented Drafting and Manufacturing) software equipment licenses from Lockheed thus becoming one of the very first CADAM customers.
1976	United Computing, developer of the Unigraphics CAD/CAM/CAE system, acquired by Mc Donnell Douglas Company.
1977	Avions Marcel Dassault assigned its engineering team the goal of creating a threedimensional, interactive program, the forerunner of CATIA (Computer-Aided Three-Dimensional Interactive Application).
1979	Boeing, General Electric and NIST develops a neutral file format as a contract from Air Space called IGES (Initial Graphic Exchange Standard).
1981	Unigraphics introduced the first solid modeling system, UniSolid. It was based on PADL-2, and was sold as a stand-alone product to Unigraphics.
1982	• CATIA Version 1 is announced as an add-on product for 3D design, surface modeling and NC programming. • AutoCAD Release 1.0 was launched. • A company called P-CAD released a CAD program called CADplan. Later the product was purchased by CalComp and renamed CADVANCE.
1983	• Unigraphics II introduced to market • AutoCAD Release 1.1 was launched. • AutoCAD Release 1.2 was launched. • AutoCAD Release 1.4 was launched.
1984	AutoCAD Release 2 was launched.
1985	• CATIA Version 2 is announced with fully integrated drafting, solid and robotics functions. • CATIA becomes the aeronautical applications leader. • AutoCAD Release 2.1 was launched. • Diehl Graphsoft, Inc. is founded and the first version of MiniCAD is shipped in the same year. MiniCAD will become the best selling CAD program on the Macintosh.

1986	• Dassault acquires CADAM • AutoCAD Release 2.5 was launched.
1987	• General Motors selects Unigraphics company as a Strategic Partner • Pro/ENGINEER 1 - 1987 (Autofact 1987 premier) • AutoCAD Release 13 was launched. • AutoCAD Release 2.6 was launched.
1988	• CATIA Version 3 is announced with AEC functionality. CATIA is ported to IBM's UNIX-based RISC System/6000 workstations. CATIA becomes the automotive applications leader • Surfware Inc., ships the first version of SurfCAM, a CAD/CAM program. • AutoCAD Release 10 was launched.
1989	Parametric Technology ships the first version of Pro/ENGINEER
1990	McDonnell Douglas (now Boeing) chooses Unigraphics as the corporate standard for mechanical CAD/CAM/CAE AutoCAD Release 11 was launched
1991	• GE Aircraft Engine and GE Power Generation select Unigraphics as their CAD/CAM system • Pro/ENGINEER 8.0 - 1991
1992	• CADAM was purchased from IBM and the next year CATIA CADAM V4 was published • Pro/ENGINEER 9.0 - 1992 • AutoCAD Release 12 was launched.
1993	• Pro/ENGINEER 10.0 - 1993 • Pro/ENGINEER 11.0 - 1993 • Pro/ENGINEER 12.0 - 1993
1994	• Pro/ENGINEER 13.0 - 1994 Pro/ENGINEER 14.0 - 1994 • AutoCAD Release 13 was launched.

1995	• Dassault Systems ships ProCADAM, a shorter version of CATIA for use on NT systems. • Pro/ENGINEER 15.0 - 1995 • Unigraphics on Microsoft Windows NT debuted • First Autodesk Web site www.autodesk.com CADKEY version 7 was launched.
1996	• Solid Edge version 3 from Intergraph hits the market at the price of around USD 6000. • EDS Unigraphics version 11 with 4 new CAM modules. In August Autodesk ships Mechanical Desktop version 1.1 Camand version 11, a CAM product from SDRC. • Corel Visual CADD version 2 (a 2D program) and CorelCAD (a 3D version) from Corel. • Pro/E version 17 with a new module which allows files to be exported into VRML file format for display on the Internet. • Pro/ENGINEER 16.0 - 1996 • In 1996, it was ported from one to four Unix operating systems, including IBM AIX, Silicon Graphics IRIX, Sun Microsystems SunOS, and Hewlett-Packard HP-UX.
1997	• AutoCAD Release 14 was launched. • TurboCAD Professional version 4 from IMSI. • VGX technology from SDRC provides intuitive interaction for the design and modification of parametric feature - based solids. It will be used first in I-DEAS Master Series 5. • Pro/ENGINEER 17.0 - 1997 • Pro/ENGINEER 18.0 - 1997 • First version of IDEAS Artisan Series from SDRC, fully compatible with Master Series, priced at ~ USD 5,000.

1998	• An entirely rewritten version of CATIA, CATIA V5 was released, First version of IronCAD for VDS market. • Solid Edge version 3 from Intergraph with more than 150 new features. • TurboCAD Professional version 5 from IMSI. • Pro/ENGINEER 19.0 - 1998 • Pro/ENGINEER 20.0 - 1998 • 1998, V5 was released, which was an entirely rewritten version of CATIA, with support for UNIX, Windows NT and Windows XP since 2001
1999	• Unigraphics Solutions signs five-year, $43 million contract with Boeing for CAD/CAM Software • In June Pro/E 2000i was launched. • Pro/ENGINEER 2000i - 1999 • Unigraphics Solutions Acquires German high-tech Company, dCADE. • March - Dassault Systems introduces CATIA Version 5. • AutoCAD 2000 was released.
2000	• SDRC, a global supplier of e-business collaboration solutions for the product lifecycle, announced on March I-DEAS 8, a major software release to enable edesign automation. • Dassault Systemes and announced the readiness of CATIA Solutions Version 5 Release 3(b) (V5R3) for Microsoft Windows 2000 operating platform. • PTC announced two major updates to its PTC i-Series of flexible engineering solutions: Pro/MECHANICA 2000i² and Pro/DESKTOP 2000i².

	• Dassault Systemes announced that it plans to integrate Microsoft's Visual BASIC for Applications into its products, including SolidWorks, CATIA, SmarTeam, ENOVIA, and DELMIA.. • IBM and Dassault Systemes launched Version 5 Release 5 of CATIA, to be available for Windows and UNIX. • Delcam has been the world's leading specialist supplier of NC machining software and services during 2000. • Second position is Hitachi Zosen followed by Cimatron. • SolidWorks 2001 • Unigraphics Version 17 was launched. • Pro/ENGINEER 2000i2 - 2000 • AutoCAD 2000i was released.
2001	• SolidWorks 2001 Plus launched • SDRC I-DEAS was bought by its competitor, Electronic Data Systems Unigraphics Version 18 was launched. • Pro/ENGINEER 2001–2001 • AutoCAD 2002 was released.
2002	• SolidWorks 2003 was released. • Unigraphics NX was launched. Pro/ENGINEER Wildfire 1.0 - 2002 AutoCAD 2003 was released.
2003	• SolidWorks 2004 • UG NX 2 was launched • AutoCAD 2004 was released.
2004	• SolidWorks 2005 • EDS sold off its EDS PLM Solutions business to the private equity group of Bain Capital, Silver Lake Partners, and Warburg Pincus in 2004. The company resumed operating under the UGS name following the private equity sale. • UG NX 3 was launched. • Pro/ENGINEER Wildfire 2.0 - 2004 AutoCAD 2005 was released.

2005	SolidWorks 2006 (Native Windows x86-64 version was released from SP4.0 onwards) • UGS purchased Tecnomatix Technologies Ltd. • AutoCAD 2006 was released.
2006	• SolidWorks 2007 (A Beta version for Vista exists with limited support.) UG NX 4 was launched. • Pro/ENGINEER Wildfire 3.0 - 2006 AutoCAD 2007 was released.
2007	• SolidWorks 2008: Includes full support for Vista x86. Out in October, 2007. SP3.1 includes native Vista x64 support • UGS was purchased by Siemens AG in May 2007, and was renamed Siemens PLM Software. • UG NX 5 was launched. • AutoCAD 2008 was released.
2008	• SolidWorks 2009: Released September, 2008. Includes native Vista x86 and x64 support. Final update is SP5.1 • Solid Edge with Synchronous Technology was launched. • Dassault announced and released CATIA V6. • Pro/ENGINEER Wildfire 4.0 - 2008 AutoCAD 2009 was released. • 2008, Dassault announced and released CATIA V6.While the server can run on Microsoft Windows, Linux or AIX, client support for any operating system other than Microsoft Windows is dropped
2009	• NX 6 was launched by SIEMENS PLM Softwares. • SolidWorks 2010: SP0.0 Released October, 2009. • Solid Edge with Synchronous Technology 2 was launched. • Pro/ENGINEER Wildfire 5.0 - 2009 • AutoCAD 2010 was released on 24 March 2009. • NX 7 was launched by SIEMENS PLM Softwares

2010	• AutoCAD 2011 is launched on 25th March 2010. • NX 7.5—launched in mid 2010. NX 7.5 to include more industrial design enhancements to make styling easier. • Creo element pro R 5.0 launched in2010.(Pro/Engineer)
	• SolidWorks 2011: Launched in jun 2010. • November 2010, Dassault launched Catia V6R2011x, the latest release of its PLM2.0 platform while still continuing to support and improve its Catia V5 software
2011	• AutoCAD 2012 is launched on 22 march 2011. • NX 8 is launched on 17th october 2011. • SolidWorks 2012 is released on 10 october 2011. • Creo 1.0 launched in 2011.(Pro/Engineer) June 2011, Dassault launched V6 R2012.
2012	• AutoCAD 2013 is launched on 27 March 2012. • SolidWorks 2013 released in September, 2012. • Creo 2.0 launched in 2012.(Pro/Engineer)
2013	• AutoCAD 2014 V-19.1, is launched on 26 March 2013. • SolidWorks 2014 released in october, 2013.
2014	• AutoCAD 2015 V-20.0, is launched on 27 March 2014. (29th Release) • Creo 3.0 launched in 2013.(Pro/Engineer) • SolidWorks 2015 releasing in october, 2014

Figure 2 .17 CAD CAM timeline
Information (Jassi, 2014).

2.2. Design and process, the role of computers

2.2.1. Introduction

This section seeks to review the typical definition of a design process by mapping a path through some well established models of design. Attempts are made to clarify the integration of computer-based technologies within systems, offering examples from leading exponents of design methods such as those discussed through the work of Pahl and Ohsuga. The intent is to provide the context for a more in depth discussion of the relationship between the design process and the technology of the production line that might allow for further efficiencies in concurrent engineering and opening opportunities for further investigation of integrated design and manufacture.

In the modern societies of the 21st century, mankind is surrounded by all kinds of engineered products. On a daily basis, we all use countless products, tools and spaces which are 'designed for the purpose'. Nonetheless the act of design is not a phenomenon of recent years, decades or even centuries; it is demonstrable that the history of design dates back to a time when early man started to make basic tools for hunting or plan for a safe night's sleep in the wild. The humans' desire and need for 'design for purpose' has not changed over history, but as time passes the methods of design, the way of designers' think and ultimately the resultant products are dramatically becoming more and more complicated. Procedures are becoming more productive and the products more efficient. Nowadays, daily presentation of improvements in various aspects of design makes the products which have been designed and produced some few years ago appear to be outdated compared to today's products [Figure 2 .18].

In the path to achieve efficiency and productivity and to cope with complicated obstructions to design and production, engineers have benefited from computers as machines which can speed up data processing and calculations and which provide rapid communication to facilitate design, management, planning, supply, fabrication, distribution and recycling [e.g. BIM systems which are discussed later in chapter 2.11.].

Figure 2 .18 Samsung phones Fast development of technology....
Left: Samsung Galaxy S4 released in 2013. Picture (GSMArena, 2013)
Right: Samsung SGH-Z700 released in 2005. Picture (phoneArena)

2.2.2. Design strategies

To discuss the production process the best way is to start from the beginning and study the roots. Needs are the generators of innovation and production. In order to address a need through innovation and design, engineers prepare a 'Design Brief' which defines the need and the required features of the desired product. Researchers can help designers build a comprehensive knowledge about the subject. Their hypothesis and experimental work opens new horizons in the minds of designers which may have not been realised or had been previously ignored. Research can also help introduce new materials or technical advancements which can enhance the level of design and production. The design brief, accompanied by related research form the foundation for designers to develop their ideas and create the best functionally and economically possible design proposal. In every proposal there is always the possibility of mistakes and unexpected problems. Analysts study the proposal and break it down to smaller elements; consequently, they can map errors and malfunctions within the design. Using design analysis and prototyping techniques, product developers can modify the product and run finetuning processes before finalizing the design proposal in detail(Pugh, 1990).

After the confirmed design, comes the next stage which can be seen as a transition from design to production. Conventionally, Process Planning can be regarded as the overlap of two major phases of design and production [Figure 2 .19]. The reason is that the work being done in this stage is closely related to both design and production. Traditionally it is not similar to either of them, yet, organizational plans are truly essential links that connect the design to production and to lead the way to manufacturing.

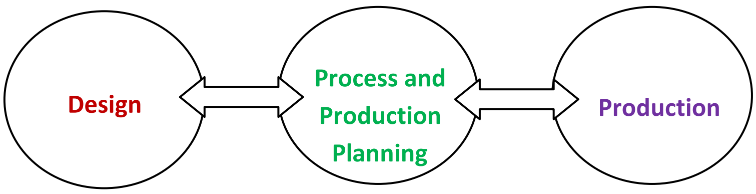


Figure 2 .19 Design-plan-production
Planning process connects the design and production phases in a traditional production system.

Process planning is the act of identification of those required procedures, technologies and actions in order to fabricate components and pull them together to produce the intended artefacts. This plan has to be processed based on the production line intended to be used. Planning for production integrates the process plan and the design proposal into a timeline, based on the factory potentials and limits(Nam, 1990). [More of organizational planning is going to be discussed in chapters 2.6, 2.7 and 2.8]

In fact, all the factors mentioned above can be seen as a very simplified view of the design process. Going deeper into the details of every aspect of the production course, shows that existing stages and their details can be fundamentally different in every production system and from one product to another. The complexity of each part of the process and the number of operations involved is directly connected to the complexity of design and fabrication(French, 2010).

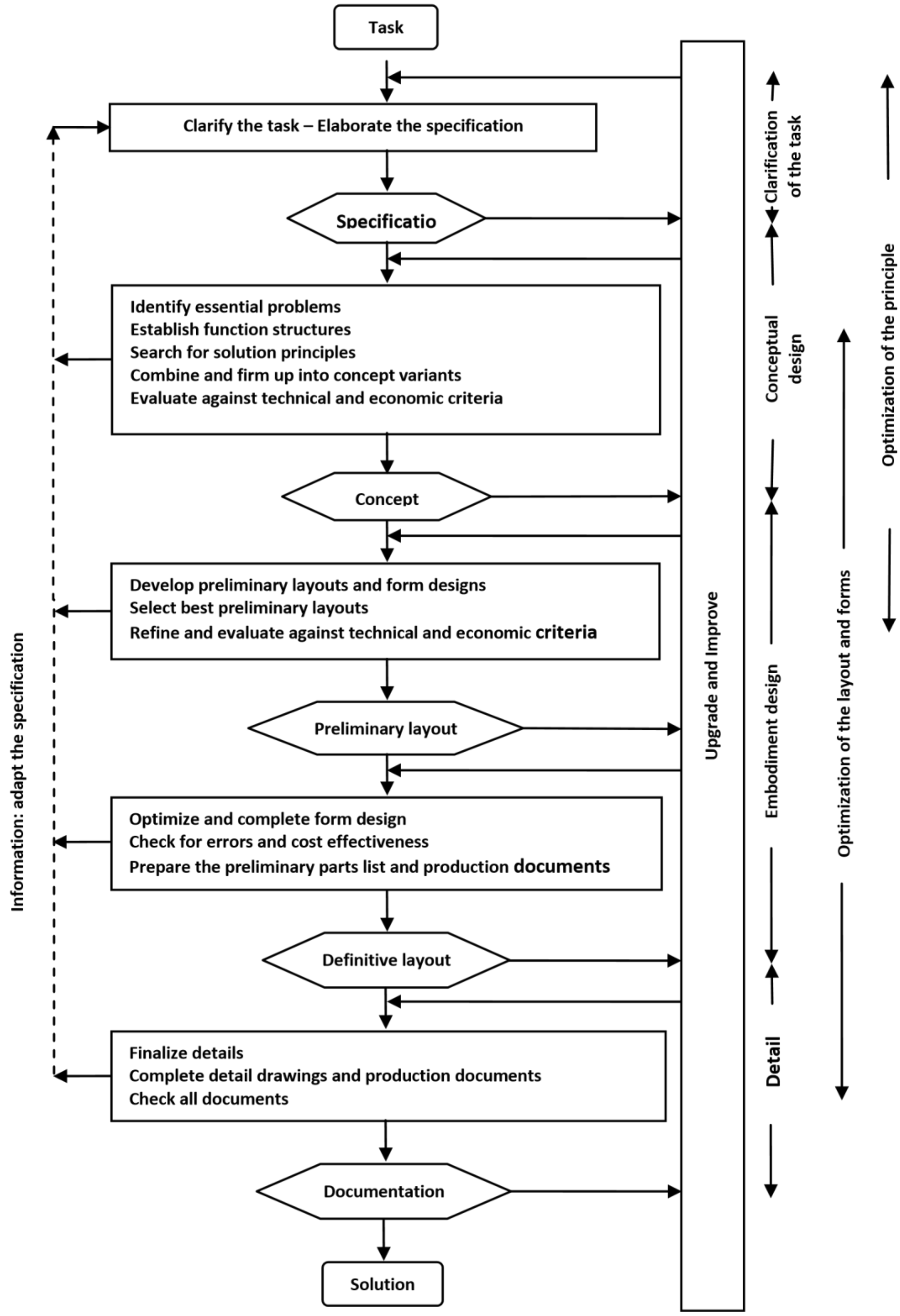


Figure 2 .20 The Pahl and Beitz model

Pahl and Beitz flowchart, defining the design process in 1984 (Pahl & Beitz, 2006).

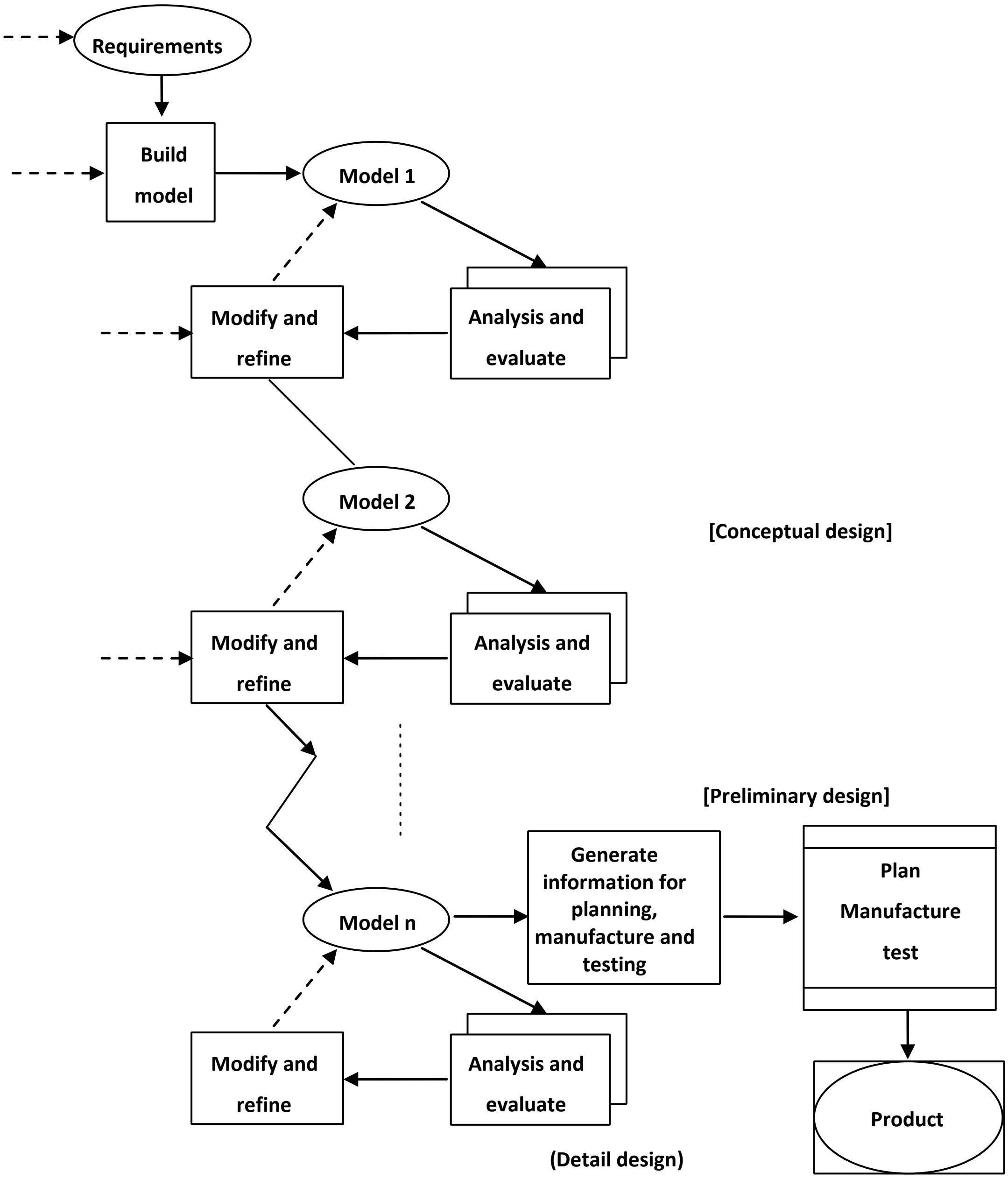


Figure 2 .21 The Ohsuga Model

Ohsuga model of design process released in 1989 (Ohsuga, 1989).

Throughout recent decades, there have been many efforts to initiate a universal method of design and production to be used in all design projects which seek to divide the whole process into certain steps and define a standard procedure to link them together. Despite all of these endeavours, until now there is not one design and fabrication process within which all details are approved by all experts so as to be declared as a standard procedure(Tunstall, 2006). There are many ways of conceptualising the process which vary in details but almost all can unanimously agree on those key process elements which start from an expression of a need then pass though many filters of analysis and the generation of a complete knowledge in regard to the implicit set of problems, constraints and solutions, followed by fabrication, investigation and application. The most recent paradigms recognise and include more elements into the previous way of thinking which support the lifecycle of the product and ultimate recycling.

In 1984 Pahl and Beitz published a methodical design approach [Figure 2 .20], defining the design process (Pahl & Beitz, 2006). Key elements of their concept are demonstrated below:

- **Data collection:** gathering knowledge about the need, problems, limits and restrictions
- **Concept generation:** investigating possible answers
- **Formation of the design proposal:** transformation of the theoretical possibilities into controlled reality
- **Refinement and development:** to finalize the design proposal with analysis, measurements, supplies and features of every piece of the artefacts.

In such systems the organization of the process is based upon the product where its production is based on a requirement to serve those exact needs of the users which were initially highlighted and investigated. Designers can categorize components of the product based on the features that suit the design process in order to simplify it. More complicated components also can be broken down into smaller, less complicated parts to ease design and fabrication. Nevertheless although such a

subset of components can be easier to design yet, it may cause some problems in the fabrication process unless appropriate strategies are in place(Pahl & Beitz, 2006).
It can be seen that apart from the key stages of a design process, the flow of the process is also demonstrated in the model. This additional layer to the design model plays a key role in increasing the quality of products and the efficiency and productivity of different teams in every stage of the process and ultimately throughout the whole project. A well tuned model of the design process can guarantee the success of projects due to the fact that a suitable model can link different teams and organize the tasks within a suitably hierarchical structure.

Five years later in 1989 Ohsuga released his model of a design approach(Ohsuga, 1989). As illustrated in Figure 2 .21 and in a similar way to the previous model, the gradual evolution of the design happens through several stages of modelling, analysis and modifications.

In this method repetitive iteration of each activity develops the concept and design. In each stage, the model circulates between different parties until the designer decides that it is ready for more detailed work and takes the model to the next stage. This flow of work continues right to the end where the finalized design proposal is ready. Again at this point the process and production planning method delivers the design to the manufacturing plant for production.

The increasing pressure for faster processes imposed by market demands has made large scale companies attempt to conclude their research, design work, analysis, refinement, process and manufacturing planning stages almost at the same time. The two design trends which have been described above, when compared to current themes in design are notably old-fashioned. In response to the needs of the modern market they do not have much to offer. In addition, major changes happening in manufacturing systems make traditional practice less and less compatible with the new systems. In return relatively new methods known as ‘Concurrent Engineering’ seem to offer the best response for demands and changes at the moment(Cross, 2008). Different aspects of concurrent engineering which are influential in many stages of the production process are going to be discussed in chapters 2.6 and 2.7.

2.2.3. Design models and systems of communication

First and foremost it is important to know that in a design project there can be many fundamentally different families of models which may define the design approach or establish the process of the design development or can only be models which just represent the design proposal. Any product while being developed in the design phase is a virtual entity. Designers use various kinds of metaphors encapsulated in virtual or physical models [known as 'Representation' methods] to demonstrate their ideas and transfer data amongst themselves [communication] and to be able to analyse, measure the qualities of the design, modify concepts and improve them with added details [Documentation] or many other purposes. Since the design method, the nature of the intended products and the complexity of the designs are different in every project, representational methods may vary from a simple concept in the designer's mind to a multimedia combination for a situation involving greater complexity(Dym, 2012).

Representation is one of the participant tools in the design process that has a constant presence in all stages of the production process. For example in the Pahl and Beitz model: the research team gathers information with the focus on needs and problems and transform this data into parameters and through them communicates with the designer who is then tasked with findings solutions which fulfil the stated requirements. These actions are expressed through 2D and 3D drawings or 3D virtual or physical models which provide sufficient information for analysts to run evaluation tests and suggest required amendments to the design group in order to modify the design proposal. A wide range of representational methods, from technical drawings to prototypes can be used for analysis and preparation of fabrication data or even pre-production marketing(McMahon & Browne, 1998).

2.2.4. Simultaneous and efficient

Despite all of the technological improvements, technical drawings are still the most widespread method of representation to be used for documentation, records and communication among all of the other different groups in every production stage from pre-design and conceptual design to manufacturing and recycling preparations. Analysts and testers as a part of their job map errors and highlight aspects of the design which need alternation and improvement. Typically they return the drawings accompanied by analytical comments to the designers for amendment. This means that they should solve the problems and then reissue an updated version of the proposal. In most cases of very complicated products such an exchange happens more than one time and not just for design purposes but also for fabrication adjustments. This continuous pattern of trial and error is considerably time, cost and labour consuming. On the other hand simultaneous systems which focus on increasing productivity and efficiency try to group several consultants who are experts in every aspect of design and fabrication of a certain product, eliminate the wasteful course of trial and error and produce a flawless piece of design work through the seamless collaboration of specialists right from the initiation of the project in order to avoid any single defect in component compatibility through miscommunication amongst different parties, in a similar manner to what happens, for example, in a gradual evolution system(Hartley, 1998)(Nevins & Whitney, 1989).

Like most conventional methods, concurrent engineering is not limited to the design phase and the system can also be seen as being applicable to pre-production and manufacturing stages. Unlike an 'over the wall' scheme [do your part and throw it over the wall for the next group] where process planning is being pursued in several separate stages and the potential for miscommunication is the largest disadvantage, simultaneous systems create a firm connection between all groups and factories. In the Figure 2 .22 a schematic comparison of conventional approaches and simultaneous engineering is illustrated(Prasad, 1997).

Although a concurrent flow of work has many positive features, it is not always an optimal choice; especially in cases which need unusual product planning and development. In these circumstances before starting on the production planning and other lifecycle issues, designers may need to primarily focus on unfamiliar or less well understood functional aspects of a novel design proposal until becoming assured about the feasibility of design and compatibility of all components(Aitsahlia, et al., 1995).

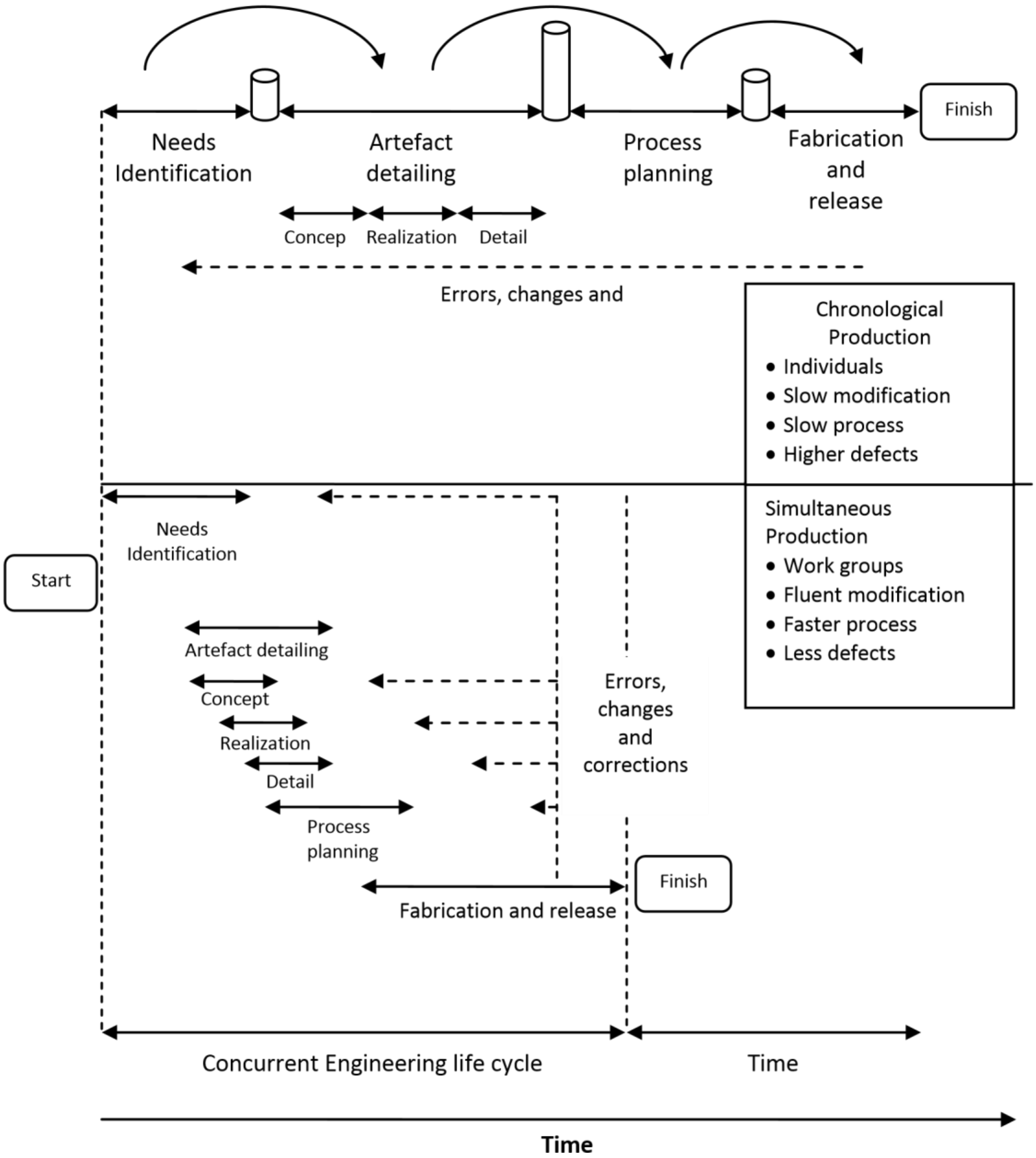


Figure 2 .22 Sequential and concurrent

Comparison of the sequential and simultaneous production. Extracted from (Prasad, 1997).

2.2.5. CAD models

Nowadays models of all kinds clearly play a key role in all design projects. Using these models, designers are able to develop their designs from initial concepts to fully detailed proposals and then prepare them for fabrication. These models are represented through various types of media and associated metaphors. Information presented within the design model can be seen as an established source of data with which to test the design proposal for desired features.

By reviewing a simultaneous engineering oriented system it can be seen that many different types of design models are being used throughout the process. In many cases several models are being made or modified at the same time. While the model of physical features and dimensional details are under development, there is often opportunity for the concurrent development of other models containing (McMahon & Browne, 1998):

- Clients' need and expectations which change during the process
- Feasibility limits
- Environmental impacts from the intended product
- Comparable features of the product for simulation and tests

In a 'Computer-Aided Design' system digital technology is a powerful tool when used to share knowledge which concern various aspects of the project and which can also provide the functionality to create further design models for a variety of allied purposes. Basically, computers are capable of processing and storing data for the purpose of (Schodek & Bechthold, 2005):

- Representation and documentation
- Generation, simulation and evaluation

What made computers the favourite tool for representation and documentation [computers are currently mainly dedicated to serve these purposes especially in small projects] is the automation of the drafting process and the elimination of recurring procedures in drafting where users can copy and modify similar components of any product instead of drawing them by hand repeatedly. In addition these machines compute data with both great speed and accuracy thereby increasing the productivity of the design process and raising the quality of products. Dealing with complicated designs [such as curved surfaces] is also an important aspect of the machines' capabilities. In many cases humans are not able to process complex geometries accurately; in other words it is getting harder to create complicated volumetric models without applying computers.

Currently, there is not much evidence of computer use throughout the very initial stages of design. This is because of a lack of precise information about the desired qualities of the products. A computer functioning in the role of a design generation tool is totally reliant upon given parameters and human intervention. After all they just process and analyse provided data based on constraints which are defined by us, the human(Kolarevic, 2005).

2.2.6. Constitution of Computer-Aided Design

CAD whether being regarded as a tool or a system, has been formed by elements namely (Ingham, 1990):

- Electronic devices, also known as visible parts of a computer or hardware
- Applications and programs which organize the work of hardware to serve a certain purpose known as software
- Raw material or information which needs to be processed. Information can also be produced by computers which used some data primarily. user interaction

Basically Computer-Aided systems are computer applications which are empowered by computer hardware. Figure 2 .23 shows the hierarchy of a computers function throughout design. Elements of computers' work in computing data can be (Kolarevic, 2005):

- creation of virtual models of geometric measures

- design evolution and improvement
- visualization for the purpose of communication and presentation
- operator interface as a bidirectional communication to input data and receive feedback
- Documentation and keeping records of information to create a virtual base for all parties referral.
- Analytical elements which extract data for different intentions
- System tools which are not influential on the geometry of design but define parts of the process such as machining details in manufacturing.

The data processing can be performed by a single software package or in some cases several compatible computer programs can process information. A program may also have access to several resources to gather data or store all information in one database(Krygiel & Nies, 2008).

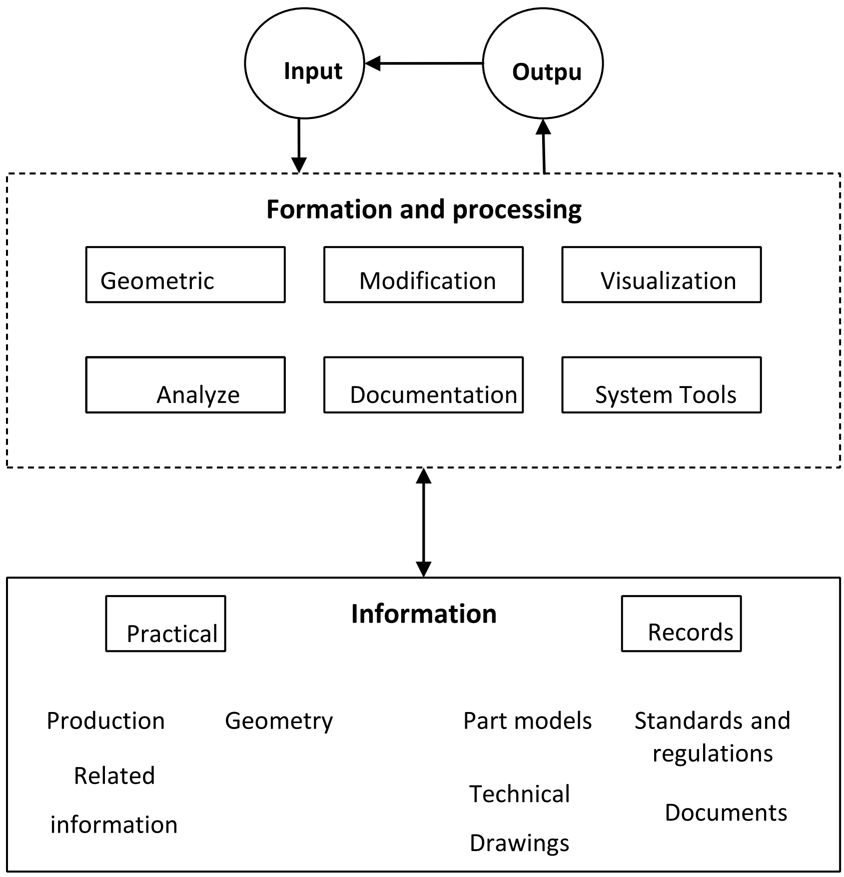


Figure 2 .23 CAD systems

Schematic definition of a CAD system (McMahon & Browne, 1998).

2.3. Conventional and digital geometric models for design

2.3.1. Introduction

In the previous section some approaches to the design problem, exhibiting common stages of design that are shared by different systems have been discussed. It has also been mentioned previously that apart from the design proposal models [popularly the geometric model of products are represented by technical drawings] there are models which define the engineering process and strategies of design and fabrication in which information can be held using a variety of types of media such as charts and flowcharts. A variety of representation techniques which are comprehensible by the whole system can be used as a common language to connect stages of the process and different parties.

This chapter attempts to study the methods which have traditionally been used as representational tools to imply the volumetric formation and geometrical details of the intended product. It also demonstrates the quality of the integration of CAD systems into the design process in order to evolve modelling representation and consequently design.

2.3.2. Conventional representation

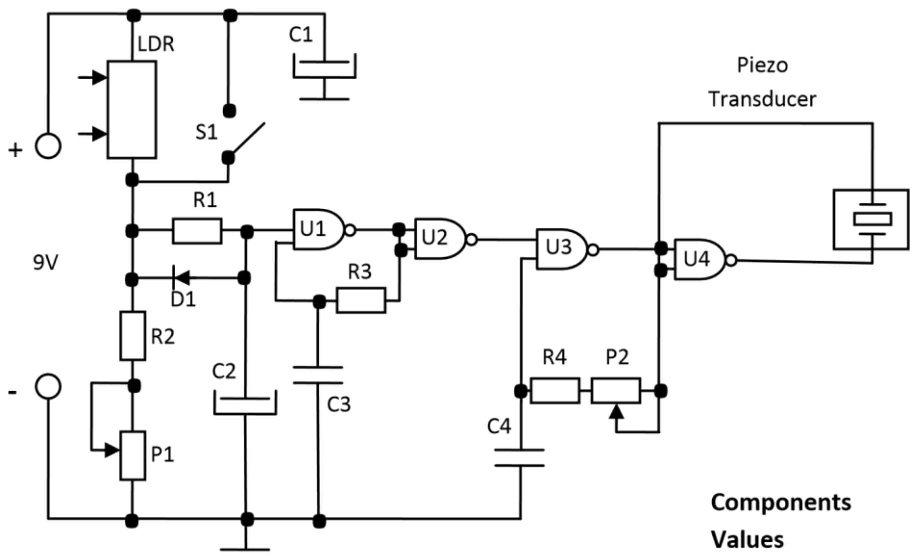
The most popular representation method throughout the past centuries has been the technical drawings. The history of Technical Drawing [known as drafting, draughting] dates back to antiquity when this representational technique was broadly used to plan and construct buildings. However, to a large extent, what we use today as a tool in our projects is a result of the work of Gaspard Monge [Figure 2 .24] a military engineer who introduced the orthogonal elevation and plan in drawings. The technique which is known as descriptive geometry is basically used to depict 3D objects in 2D projections (Baynes, 1981) (Booker, 1979). Technical drawing and descriptive geometry has become respectively the common language of design all around the world. However these flat drawings can carry very useful information which is mentioned briefly below (Wright, 2011):

- Lines deliver information about objects. Various 'linetypes', thicknesses or colours are used to differentiate function and different lines have different significance.
- Sections are views, revealing inner parts of objects
- Different views are defined based on the viewers' direction of sight
- Parallel projections are based on the original scale
- Perspective projections also carry depth of view and represent a more realistic 3D view of objects but scales are variable based on the angle.
- Drawings basically show the form of objects and can utilize added annotations which carry other data such as dimensions.

Figure 2 .24 **Gaspard Monge**
Gaspard Monge the inventor of descriptive geometry [the mathematical basis of technical] and the father of differential geometry drawing. Picture and description (Wikipedia-d, 2013).

In some cases in order to eliminate time consuming drawing of the same components, certain signs or conversations are used to substitute for complicated geometry. These signs are both ubiquitous and recognized by all people using 2D draughting techniques or may be appointed as a set of default conventions in companies (Bielefeld & Skiba, 2006).

As well as the common use of models for describing and communicating geometry the use of technical drawing has evolved a language comprised of a common vocabulary and grammar composed of symbols. Figure 2 .25 shows a refrigerator door alarm circuit diagram which uses standard symbols and annotations to represent the electrical circuit of the product. The use of well defined standards in terms of symbols and their usage is essential to avoid confusion between different parties engaged on the design process. There are many standards recognized by various institutions in which signs representing certain activities, objects and components (Bielefeld & Skiba, 2006).



Components Values

R1 = R3 = 1 M Ω	**C4 = 0.01 µF**
R2 = 1 K Ω	**P1 = 10 K Ω**
R4 = 10 K Ω	**P2 = 25 K Ω**
C1 = C2 = 10 µF	**D1 = 1N4148**
C3 = 0.47 µF	**U1...U4 = 4093**

Figure 2 .25 Schematic electronic design
Refrigerator door alarm circuit diagram (Marian, 2010).

Various kinds of diagrams exist and each of them is designed for a certain purpose. In every stage of the design process we may require some sort of them. For example if we initially want to show the hierarchy of processes or connection between components a block diagram may be the best solution Figure 2 .26.

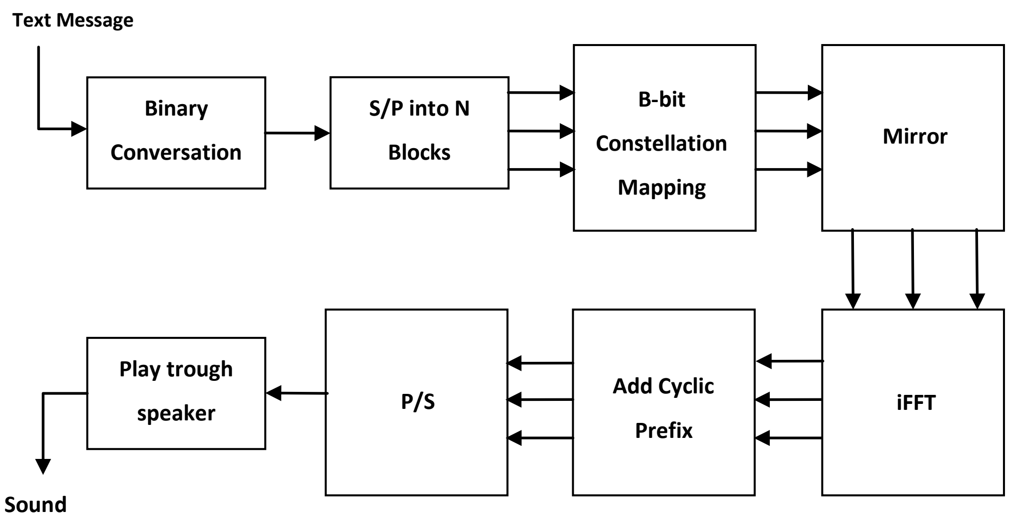


Figure 2 .26 Block diagram

Block Diagram showing a transmission system (Viel, 2009)

Using this representational tool, designers can break the whole project down into smaller components to cope with more complicated designs. The same applies to volumetric models; diagrams can develop to more detailed levels. The approach is called 'top-down' which a schematic definition of that is illustrated in the Figure 2 .27.

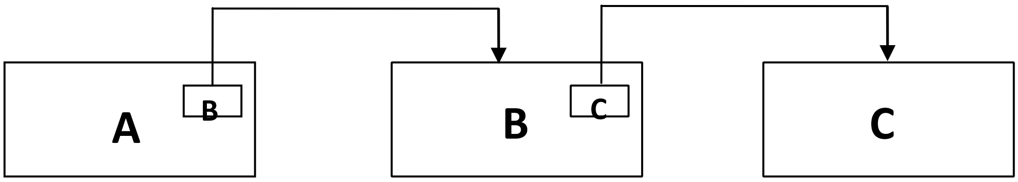


Figure 2 .27 The Top-Down approach

An approach where based on the necessity, new set of information and details should be provided to explain smaller systems which work within larger systems.

Traditional methods of representation have been effectively used for many decades in design, fabrication and in the construction of countless products due to the limited complexity of the design and the requirement for relatively straightforward processes. This also applies to almost all systems which can be planned and defined by flowcharts and diagrams. Rules or standards defining the representation framework and symbols became a common language which connects all designers, technicians, consultants and others involved in the design process.

Eventually and by the end of the 20th century fundamental shortages and constraints of technical drawings and manually designed diagrams had confined the capability of the traditional methods; they appeared to be insufficient in order to remain dominant and responsive to the new needs imposed by more recent projects. First and foremost, there is a need for persons who are trained as draftsperson that have learned how to draw symbols and know the rules and styles of a universal drafting framework or a company's own set of standards. The next most influential defect of traditional methods is the constant presence of possible misperception due to the orthogonal 2D drawings' lack of ability to represent multiple views of objects instantaneously and on demand. A simple error in using symbols may result in a dramatically different product. It is a fatal obstacle against the timescale of projects and such defect weakens the connection of different groups in design departments and the connection of the design departments to the manufacturers. Additionally each mistake calls for the redrawing of the whole set of documents. And last but not least is the inability to represent complicated designs such as curved surface as commonly used in the aerospace and car industries. Most of the time it is impossible to realize or to figure out the connections between several components in a highly complicated system while just drawing on paper and by hand [Figure 2 .28] (Simmons & Maguire, 2012).

Figure 2 .28 Manual drafting
Manual draughting is a labour intensive and time consuming process. Picture (Beutel, 2009).

2.3.3. Computer-aided representation

It has been mentioned before that the integration of computers into design and fabrication systems can introduce new solutions for processes and products, but currently they are mostly applied to advance the existing and conventional methods. These advancements have come about through the computers' ability to generate models or to add dimensional and production details based on given parameters and through elimination of recurring procedures in drawings and other representation methods. All the refinements on design models can be determined by only making changes on the existing digital model without the need to redraw the whole technical documents or rebuilding the model from the scratch. In addition, the remarkable accuracy of the Computer-Aided Representations is now becoming almost irreplaceable in production of complex products (McMahon & Browne, 1998) (Kolarevic, 2005)

The techniques and standards which are being enforced in computer drafting are similar to the rules in conventional methods. Even products of the two different techniques either being printed on paper sheets or displayed on computer screens may look the same; although the digital versions are usually capable of carrying out a lot more actions. Either prepared digitally or manually, all 2-D geometric representation models are composed of different types of lines and dots. Their length, positions, directions and angles are assigned by coordinates on the X and Y axis [Figure 2 .29].

Unlike traditional technical drawing, computer drawings are drawn in full scale. The limit of drawing size is dependant of the capacity of data storage units whereas conventional drawings are limited to the size of the drawing sheet. The ability to draw at full scale means that the possibility for errors is much less in ComputerAided drawings. In addition it is worth pointing out that the digital capabilities of digital systems have made the drafting much more efficient than other traditional methods.

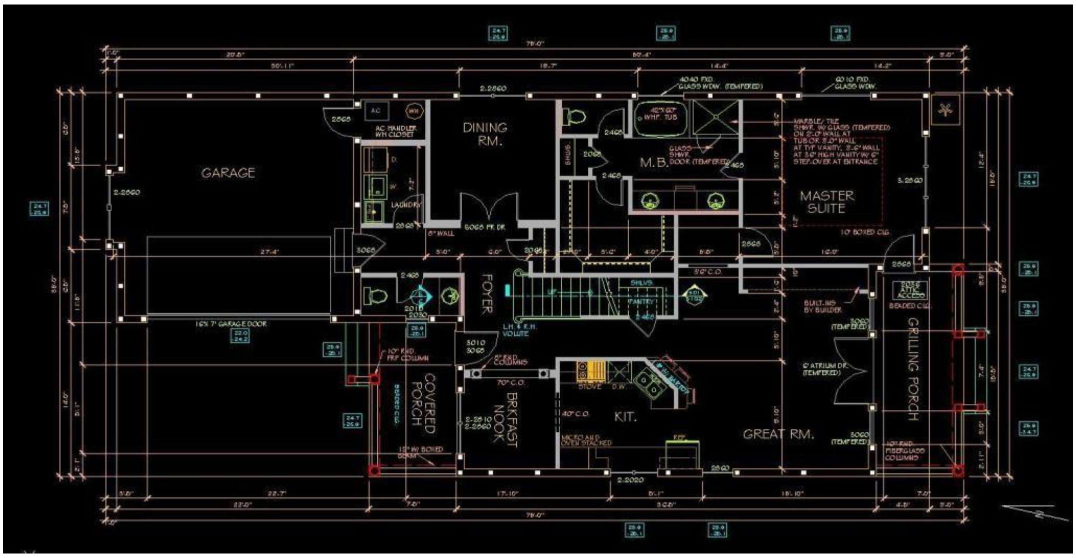


Figure 2 .29 Digital drafting

Digital drafting has almost the same appearance as the traditional techniques but digital capabilities have made it much more flexible efficient. Picture (Classical Drafting).

Using CAD applications solely as drawing tools means that most of the progress in technical drawings', methods of diagram drawing and the visual state of the drawings in computers would be similar to traditional methods. Boxes, lines, curves and connections are drawn and standard signs should be placed by operators. In many computer applications there may be some templates for shapes, symbols and connections. These, facilitate making diagrams but basic CAD applications do not carry the ability to analyze and evaluate diagrams and inform users about errors. Specific diagram production software has been developed which can be used in various industries and can characterize symbols and connections in virtual diagrams and can even replicate systems' behaviour in the real world.

2.3.4. Computer-aided 3D modelling

One of the major advancements of Computer-Aided representation and visualization is that it has given the ability to designers and operators to create virtual 3-Dimensional geometric models of products and work with a more realistic view towards evolving their designs. 3-D models provide a good volumetric understanding of an object and can help to eliminate errors caused by misunderstanding flat representations by providing real-time views from different angles on demand.

Although there are several ways to create a 3-D model, they are always produced in a GCS [Global Coordinate System, XYZ axis] using lines, curves, faces and solid components. The resulted models can be represented in a number of forms some of which can be categorized as below:

- Wire frame: a Wire-Frame model uses lines and curved segments to represent the edges of the geometry
- Planar definition: these models present geometry through demonstration of all or part of the components' inner or outer surface.
- Solid components: the first two models use two dimensional elements to illustrate a three dimensional virtual object. Those models could be used for visualization and many other purposes. But they are defective when simulation, analysis and digital fabrication are the intention. Thus a solid representation of objects is becoming more and more on demand in today's engineered design and fabrication.

So far what has been discussed was generally focused on the application of computers and digital application facilitating activities which used to be performed by hand and has also briefly introduced the extra capabilities added by the digital technology. The following sections are intended to focus more on the features which are specific to digital technology.

Part two: Design

2.4. Digital models and design

2.4.1. Introduction

The basis of relatively new CAD systems and their application to design representation and modelling has been briefly defined in the previous chapters. Chapter 2.4 attempts to illustrate the predominance of the practical application of Computer-Aided technologies exclusively in the design process and argues as to CAD's influence on design evaluation to discover the products' ability to serve the needs of the users and also how designers can program computer applications to run automated design-related procedures.

Throughout this section of the chapter, a vision of 2D and 3D representational models in projects is initially presented. Afterwards the application of CAD models in volumetric reasoning and Finite Element Modelling [FEM] is discussed which is followed by defining the expanded capabilities of CAD applications in order to fulfil user's unique needs in different application areas.

2.4.2. CAD and technical drawings

The influences of CAD on design representation such as modelling complicated objects, instantaneous production of limitless views from different angles and modification of components at any stage of design have been discussed before; yet, it is not only geometry and form that comprise technical drawings. Several groups of data accompanying the model make them operative for analysis and production (Rooney & Steadman, 1997).

Nowadays most CAD applications can enable users to categorize elements in product models in elective groups. These groups of objects and components are often called layers. Each layer may carry certain features which are defined by the designers or draftspersons and are assigned to all the elements included in that category [Figure

2 .30]. These features can be related to a wide range of definitions from thickness and type of lines [used in representation] to colours, materials, etc. [used in evaluation and production planning and machining] or even to determine what groups should be displayed or hidden in certain views and so on. This way, modifications become more easily accomplished. These methods of structuring a drawing are often defined as standards within a company or an industry and are stipulated from the outset of any collaborative design work (Kugathasan & McMahon, 1997) (Finkelstein, 2011).

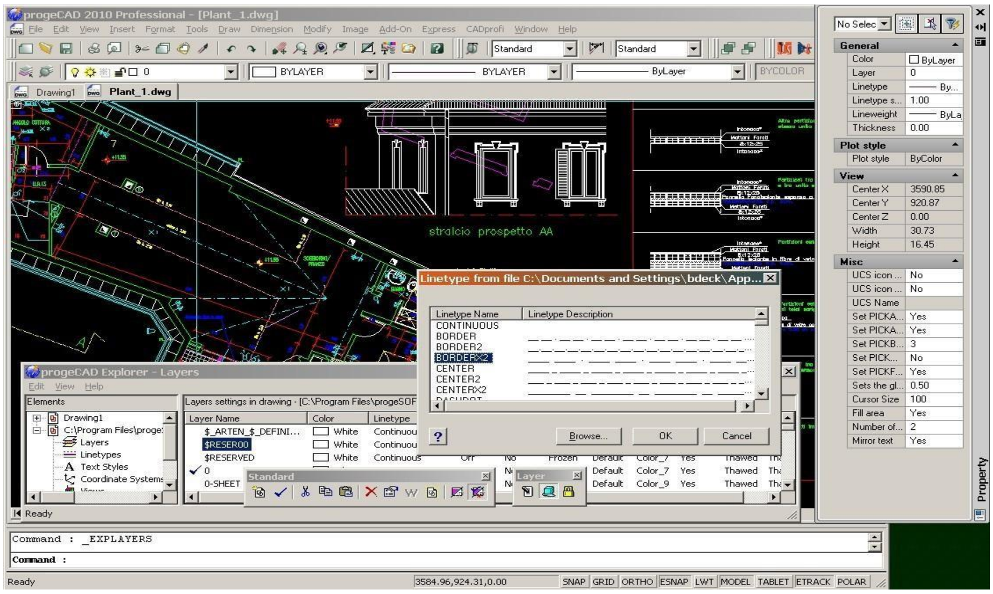


Figure 2 .30 Layers in CAD
Layer management Application. Picture (smartcode, 2012).

In every model, information packages which are added to the modelling geometry via footnotes, dimensions, hatches, etc. are essential for communication and realization of the design. CAD technology facilitates the process of adding this information and this organization of data in digital models by commands and tools which automate the process. For the task being undertaken it is only a matter of selecting objects and elements of the design by the users. The intrinsic ability to perform such actions ensures that the results are free of human mistakes and unexpected errors.

Apart from all the benefits of CAD annotating applications there are some disadvantages which are mentioned below (Ozok & Zaphiris, 2011) (Wright, 2011):

- Most of the CAD annotation applications are designed to respond to various standards; but, in some cases there are slight misfits regarding companies' drafting standards. Sometimes it takes a long time to adjust options in order to fit the desired method.
- CAD software developers try to design a versatile application by adding several standards to their systems but such broad information and style make those applications appear quite hard to use for new users.
- Most of the CAD applications allow users to annotate their designs both manually and automatically. Although the default automated tools are supposed to ease the process and make them more accurate and fast; yet, sometimes using automated CAD tools are relatively more difficult to add annotations to a busy model compared to manual methods (Figure 2 .31) (Figure 2 .32).
- CAD tools may become unresponsive when there is a simple defect in drawing.

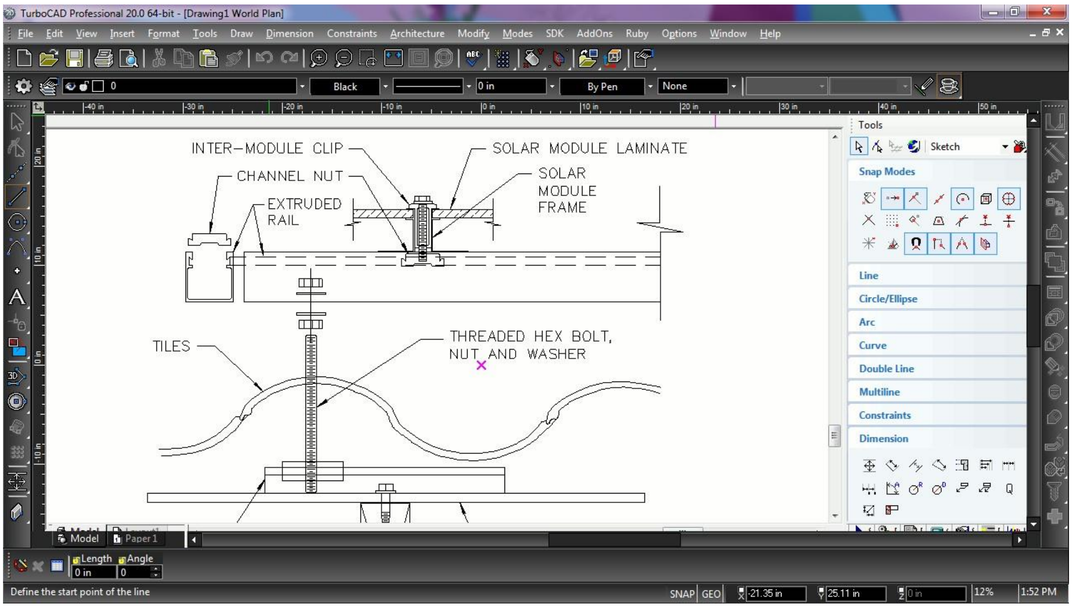


Figure 2 .31 Annotation
A manually annotated 2D technical drawing operating in TurboCAD. Picture (TurboCAD).

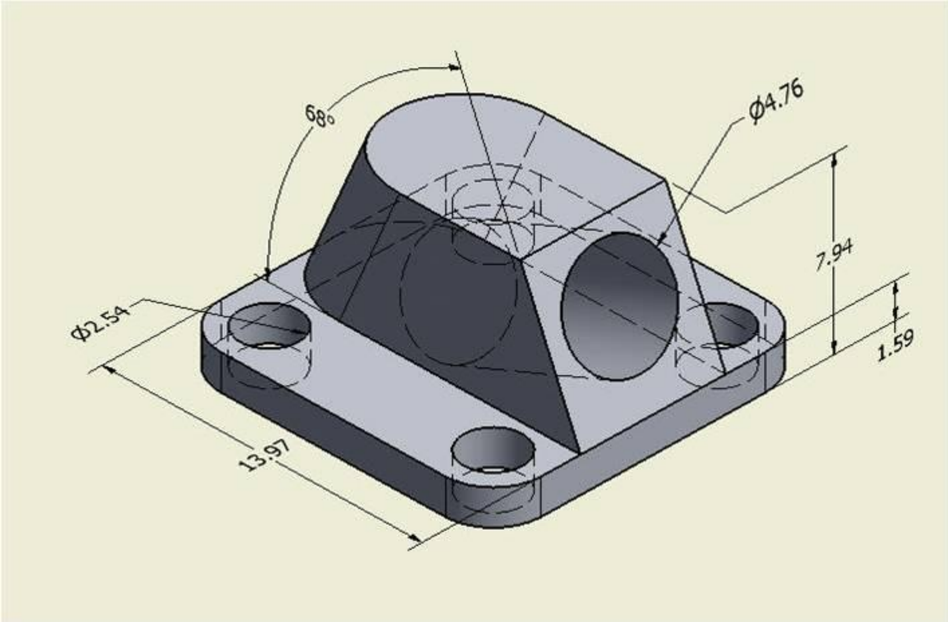


Figure 2 .32 Automated annotation
Annotation using automated CAD tools. Picture (PLM Engineering).

Perhaps one of the major advantages of CAD systems can be found in their ability to copy and paste large amount of graphical information. This could be through copying elements and lines inside a single document or importing and exporting data from and to other documents and the use of readymade templates. Functions such as rotation, mirror, copy, rescaling and many other modification tools make it possible for a draftsperson to adjust repetitive elements in the desired position [Figure 2 .33].

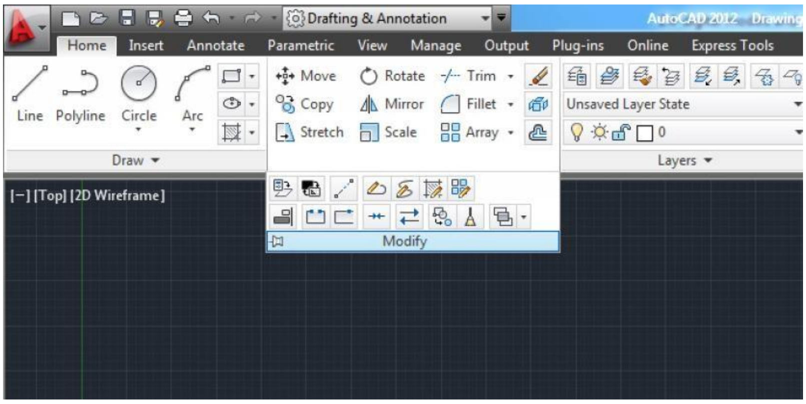


Figure 2 .33 Modification tools Screenshot illustrating the 'modify toolbar' in Autodesk AutoCAD 2012.

In more recent versions of CAD applications there are guides for users which make modelling much easier. Polar tracking, object snaps, grids and many other drawing guides keep drawings accurate as well as easier to work with [Figure 2 .34]. CAD models should be drawn accurately and to scale in order to allow automated procedures to add annotation to the design. Duplicated elements such as lines which are common in 2-D Drawings which when extracted from 3-D models can cause errors in automated procedures. Monitor displays are mostly not large enough to illustrate enough details. Although zoom tools sometimes can confuse users and be time consuming to use; they can provide views with required details in every step of drafting process for more accuracy (Finkelstein, 2011).

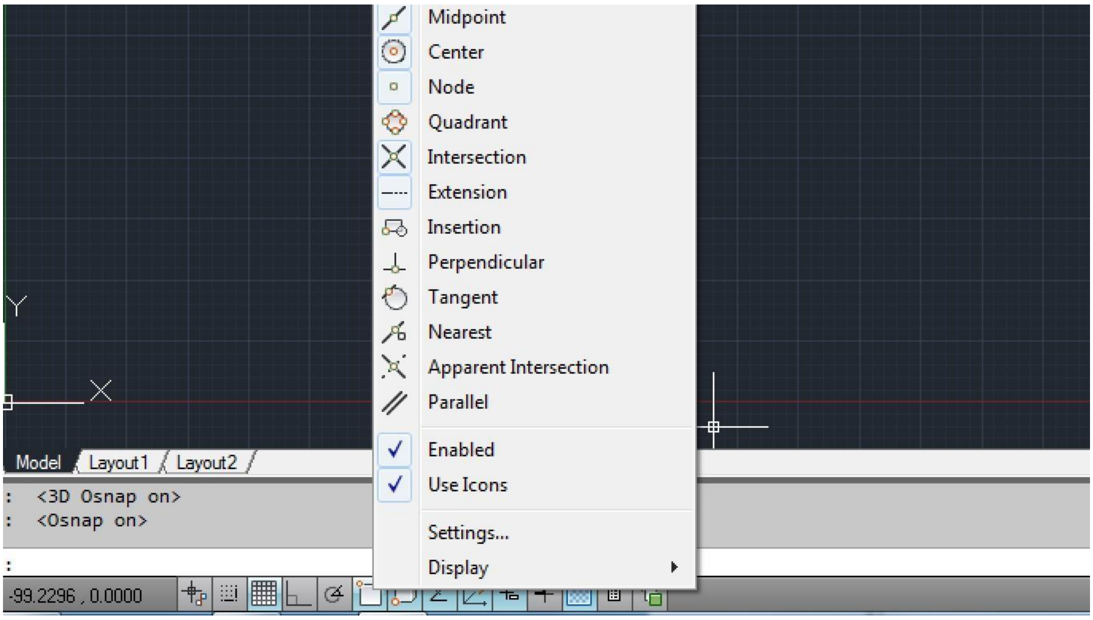


Figure 2 .34 Drawing guides
Screenshot showing the drawing guide band and some of the object snap choices in Autodesk AutoCAD 2012.

2.4.3. Three dimensional modelling in action

From the mid 20th century when the CAM concept was introduced, numerous efforts in this field have been focused on gathering all of the planning, testing and production information for every project into a single source which would be accessible for all members of the projects' teams. The fundamental element of such a core would be a virtual 3D model. Today such a system is being used in many companies and the number is growing every day. Even so, the method is arguably not as widespread as it deserves to be (Krygiel & Nies, 2008). In order to discuss the reasons it would be a good start to point out that although modelling has become easier using computers, it is also true that modelling highly complicated geometries calls for computer operators with a high level of proficiency and the use of advanced applications. Companies have to devote considerable resources to train staff based on their level of work and standards and also in the procurement and maintenance of software and peripheral systems. 3-D modelling has always been dependant on computer hardware. To run a heavy modelling project, companies have to be well resourced and need to equip their offices by very capable and up to date computer hardware supported by high capacity RAM, large storage devices, powerful CPUs and Graphic adaptors which are normally very expensive. Another weakness of the digital models is the need for the continuous presence of computers in order to have access to the models and to add or extract information from them. The latter problem is gradually being solved as numerous types of portable and effective devices are being introduced to the market almost every day. And last but not least, when the production method is not a Computer-Aided process which would be based on a direct link between design, planning and fabrication, we still need to produce 2D annotated drawings of some kind to express design features in addition to product manufacturing and construction data.

Such shortcomings of CAD applications are not permanent obstructions and have been the subject of many research projects. Software companies like Autodesk and Bentley and many others develop and progress their CAD software and release new versions in relatively short periods of time. Processor manufacturers such as ‘Intel’ and ‘AMD’ produce faster hardware components in response to the demanding market. Getting more and more involved in CAD/CAM technologies makes companies more eager to make investment and benefit from the seamless technology which would allow them to extend the levels of creativity and productivity in their projects.

Even though the application of 3D models is not definite in all design projects, but some certainty exists when we talk about (Kolarevic, 2005):

- Representing a complicated surface such as aircraft body which is not possible by traditional technical drawings.
- Abandoning the physical prototypes in order to test the design, such as what which has happened in designing the 777 Boeing. This way prototypes of many more design proposals can be tested in much cheaper ways; therefore the end product is going to be more accurately evaluated and the resulted data are more reliable and also there is going to be less waste of materials and time for evaluation purposes [Figure 2 .35]
- Computer-Aided Manufacturing which is based on 3D digital models and direct link of design and fabrication [or File to Factory technology].
- Accurate design of complicated components which is mostly impossible using traditional methods.

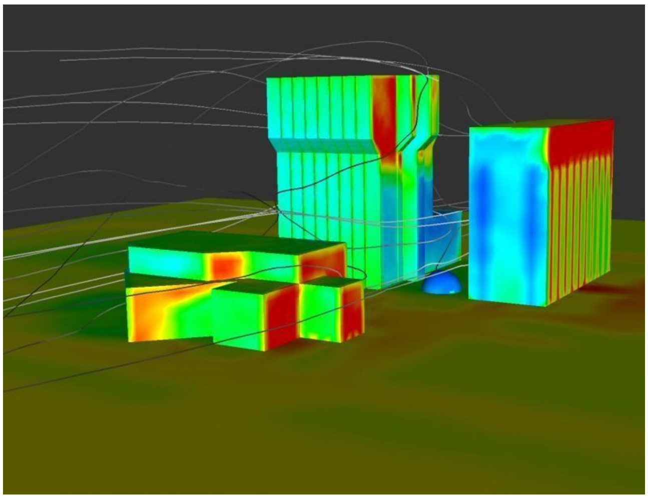


Figure 2 .35 Digital analysis
CFD [Computational Fluid Dynamics] thermal analysis software results using 'Thermo Analytics' thermal analysis software. Picture and description (ThermoAnalytics Inc.).

As previously mentioned, when working with traditional fabrication methods, various views of 3D models need to be converted to 2D, flat technical drawings with added annotation arranged in a sheet to be printed and shared with the production team.

In many of the older versions of CAD applications, raw raster images could not be used for representation and annotating and needed some modifications to fix lines which may not be in a desired segmented manner or need layer rearrangement to define design properties. However such shortcomings are becoming less relevant in the most recent versions of the CAD applications due to the persistent development and progress.

In many projects, 3D models may be used only for 2D representation; nevertheless even in the creation of technical drawings there are benefits in using 3D CAD models as follow (Autodesk, 2009):

- Clear representation of components' connections
- Production of realistic sections on demand for geometry testing
- Accurately generating flattened views of complicated skins of components also known as developed surface [Figure 2 .36]
- Ability to manipulate models and examine results to reach the desired geometry

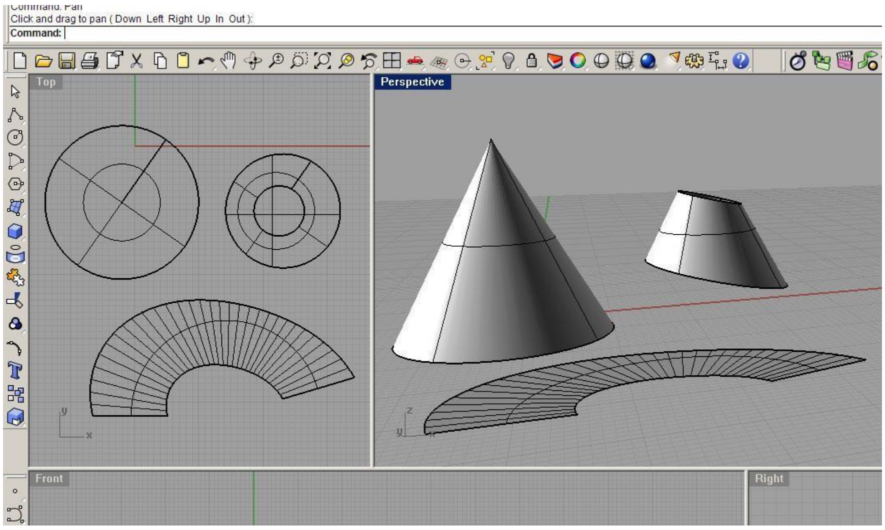


Figure 2 .36 Developed surfaces
A developed surface of a sliced cone in Rhinoceros software. Picture (Autodesk, 2009).

2.4.4. Evaluation of design

From the initiation of a design project, several models of various types each concerning certain aspects of the products are produced to create a platform for the design work and representation, however the core models are those representing geometry and structure. Other forms of models are either developed from these or would be regarded as additional information completing the geometric models. Additional models may be in the form of analytical and production engineering models.

Design proposals are subject to many tests from different aspects. These tests comprise a wide range of evaluations from material choices and the feasibility of production to the assembly of components and post production features such as stability, environmental impacts, the level of response to users' needs and even end of life disposal. Depending on the complexity and sophistication of the final products many groups of analysts and testers apply a number of methods to assess their products. Sometimes in order to test a certain feature of design it is not possible to run all the tests on a volumetric model of design and, based on given data, as it can be seen in Figure 2 .37 engineers can produce a secondary duplicated parametric model of components to gather the necessary information (McMahon, et al., 1995). Other sorts of secondary models exist which may be produced in any stage of the design and planning process as needed. Their existence can be based on their application which can be temporary or long lasting [e.g. models of product lifecycle]. In some cases tests may be run on each component separately, whereas sometimes the work of one component is influenced by the work of some others. In this case the whole system is usually divided into subsystems and technicians run tests on each subsystem to analyse constitutive components (Kolarevic, 2005).

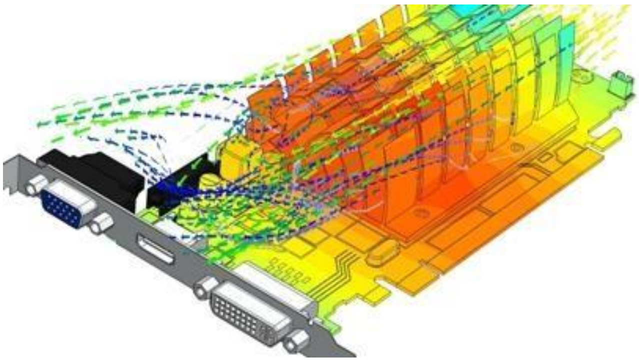


Figure 2 .37 Digital evaluation

An illustration showing the result of thermal evaluation of Graphic adaptor chipboard used in personal computers prepared using a parametric model carrying heat production features of the board's components. In this case there can also be a model showing electrical circuit of the parts. Picture (Electronics Weekly.com, 2013).

Finite Element Method [FEM], amongst all of the evaluation techniques, is an example of a powerful method, capable of providing comprehensive results by running tests on design proposals and products in regard to various aspects of technical, performance-based and volumetric features and is highly popular among designers and manufacturers.

The basic concept of the finite element analysis is to deal with highly complicated problems by breaking down the whole system into smaller parts and solve the problem in each smaller component individually. The sum total of the results of individual analysis of parts is an approximation of the answer for the whole system. In this concept the small elements which form the totality of systems are named as Finite Elements (Mottram & Shaw, 1996). Basically in a FEM analysis system, large problems are divided into smaller problems which could be resolved much more easily. This technique may be used in design and manufacturing of complicated forms and objects. In order to design and manufacture a complicated forms such as multi curved surfaces, they could be broken down into more manageable shapes which allow more accurate calculations and therefore improves the feasibility of the realisation of such complicated forms for example in building construction.

2.4.5. Spontaneous design organizations

CAD systems have been designed and developed to facilitate the design itself and broaden the limits of product design and feasibility of production. Some users take it even further and begin to modify CAD applications to integrate them more into their type of requirements and thereby switch repetitive, time consuming routines into an automated system of work. Nowadays organization modification and customization is a crucial activity in the work process of many companies to benefit from the most celebrated strength of many CAD applications.

In cases where the same elements or geometries are being used, the role of customization and programming may be just a step in the design. Whenever there's a similar standard in a process it can be automated to save time. At a more advanced level designers extract the grammar of their design and define its features and constraints by parameters and variables of the context. When a situation changes it induces changes upon the variables and parameters, thus the result fits the new constraints as well as the design's fundamental concept. During recent years a large amount of research has been conducted towards the development of the Knowledge-based systems which can run analysis, extract data and modify design based on varying parameters. Advancements in the realm of the Artificial Intelligence technology and robotics have also been influential on automated design procedures (Leyton, 2006) (Leyton, 2011).

2.5. CAD a breakthrough in the quality of design

The following chapter discusses an emergent view in design which considers computers as tools to automate the design, planning and engineering process. It discusses the current theme in which these approaches work and in some cases brings up some suggestions which can develop the abilities of those methods. Topics such as Artificial intelligence, Knowledge Based Engineering [KBE], parametric design and feature-based techniques are in fact extensions to generic CAD applications and serve to promote them from being just used as representation tools and so allow them to be more and more involved in the actual act of designing geometries, components, objects and planning automated fabrication process.

2.5.1. Introduction

Nowadays, it is widely acknowledged that CAD systems are inseparable elements of most of the manufacturing industries and consequently have become the mainstream of design organization in numerous companies. As has been mentioned in previous chapters, the current theme of applying such systems is not so prevalent in the initial stages of design such as conception and form generation. Computers are mainly used as tools, simulating the design geometry and processing design information about fits and CAD applications can be used to develop analytical models and provide the ability to run tests on them; yet, they do not have a direct influence on decision making about form generation or the suitability of suitable structural systems. Computers may extract fabrication and planning data and perform sequential programming but, for instance, they cannot choose materials which serve the purpose both functionally and financially due to the current reality of the market. The nature of CAD models sometimes makes them less applicable to model the geometry of products during the initial stages of design, when designers experiment with various objects and elements and forms which do not possess a tangible scale and position. Traditional paper, pencil and hand drawings are still the most favoured design tool at this stage. In general, CAD models mostly need engineering data and specified features of products to be influential and most designers in the early stages of design prefer to use hand sketches and metaphors of elements to experiment with forms and geometry because it is more creative, faster and easier to manipulate, where they can draw several sketches and compare them visually just in a few seconds (Aliakseyeu, et al., 2006).

Throughout recent years much research has been directed to the development of Artificial Intelligence as well as computer integrated systems and information technology to involve CAD more and more in the process of geometry generation. Computer-Integrated systems provide a number of alternative organizations of concepts to build a foundation for the designers' work.

The combination of these new methods and systems causes a dramatic change in the process of product design, representation, planning and manufacturing. A more recent trend in design methodology is to create several working models based on all of the necessary fields of information which are essential for the progress of work. These information or geometric based models are then used to generate knowledge as to different aspects of the project and serve to develop the concepts right down to the narrowest and deepest details. These models may gather together and form a stronger source of information with the ability to mix all of the model information in databases as a core component of a modern production systems has been developed into a new organisational concept [Figure 2 .38].This core of data can be accessible based on predefined limits for all of the projects members.

2.5.2. Computers which think?

Applications of 'Artificial Intelligence' [AI] have been widespread in a large variety of industries. For a long time mankind has been dreaming about the creation of machines which can mimic the human's physical and mental behaviours. By the time researchers conceived the concept of a computer with the capability of the human mental behaviour designers become attracted to the application of such tools in their design work. The radical effort to recreate human intelligence via computers is still a topic of debate and faces severe criticism about its practicability.

Nevertheless there is another less intensive view toward the technology which seeks the production of computers that can simulate the real world context; some aspects of this philosophy currently exist. Applications can be used to mimic the decision making process of the human mind to overcome the problems in better ways in comparison to conventional methods (Jagdev, et al., 2004).

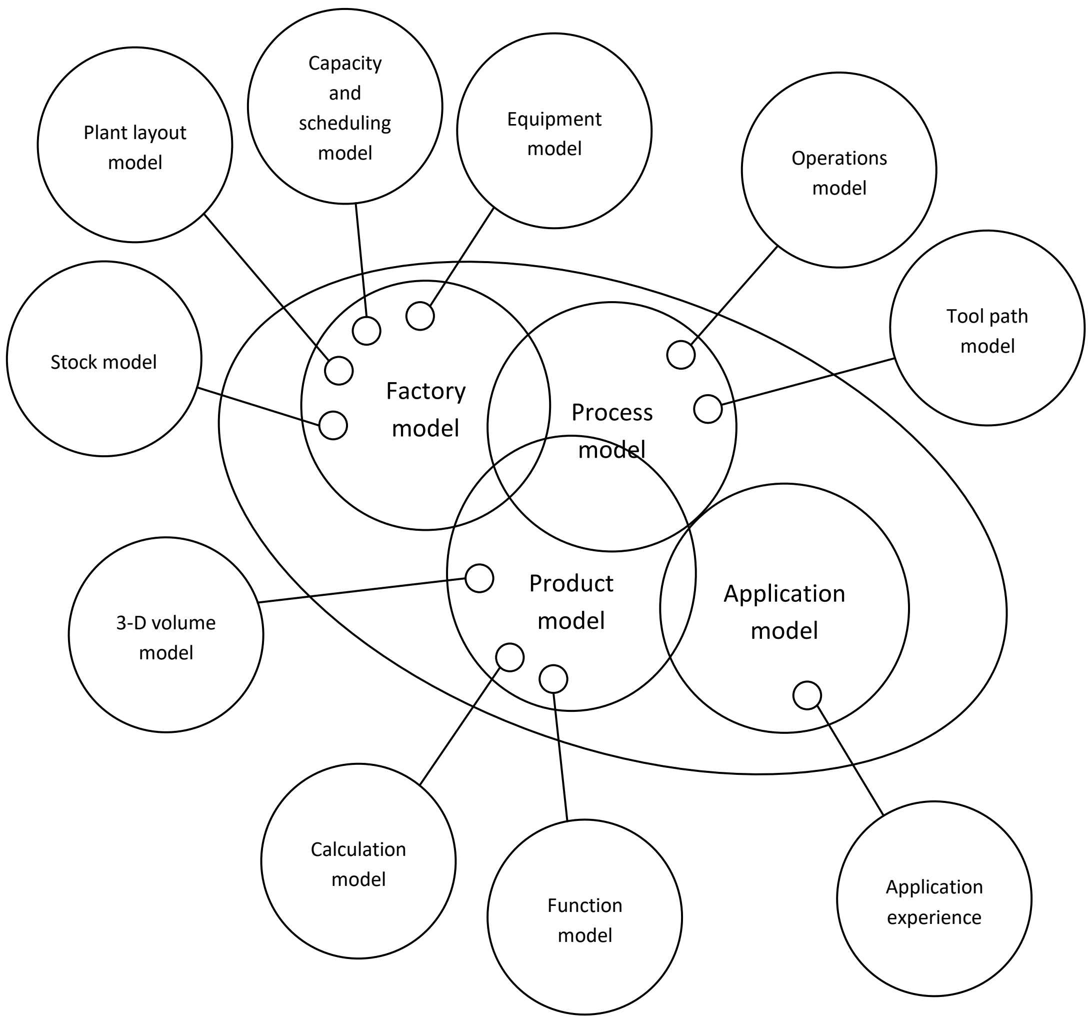


Figure 2 .38 Organizational approach
An example of organizational approaches demonstrating the connection of various models of design in a data data core. Extracted (Spur, et al., 1989).

Studies in the field of AI and its applications in design are mainly focused on computing design data and form generation, analysis, regeneration and modification based on all of the input parameters. This process depends on a logic that can turn information into different forms of representational models, as required by designers. Systems that run this kind of exploratory activity in the field of AI are known as expert systems or in a wider view knowledge based systems (Pahl & Beitz, 2006).

The term 'Artificial Intelligence' was first coined by John McCarthy [1955] who described it as "*the science and engineering of making intelligent machines*" (McCarthy, 2007). 30 years later 'Brachman' and 'Levesque' described the most significant intention of AI as "*writing down descriptions of the world in such a way that an intelligent machine can come to new conclusions about its environment by formally manipulating these descriptions*" (Brachman & Levesque, 1985). The basic feature of a knowledge-based system [Figure 2 .39] "*is a formal and explicit representation, stored in a knowledge base, of the knowledge pertaining to a given area [or domain] of activity*" (McMahon & Browne, 1998). The system represents data [concepts and protocols of relationships] using a certain language consisting of symbols and well defined metaphors which conduct system outputs. An inference Engine computes the data which has been gathered in the Knowledge base to exploit new information. The Engine's activity [e.g. finding errors in a system] is mainly based on search and comparison of the default data that has been defined by the system users.

Progression of the knowledgebase is dependent on an activity called Knowledge acquisition which is "*the transfer and transformation of potential problem-solving expertise from some knowledge-source to a program*" (Buchanan & Shortliffe, 1984). Knowledge elicitation is one of the methods which can perform such a process by analyzing the expert's performance [For instance, analyzing experts' methods of decision making in order to populate defined templates of questions and problems]. But how does AI integrates with the design business? 'Knowledge-based' and 'Rulebased' methods can run the design process through the automation of routine activities of decision making and problem solving where based on certain rules which have been defined by users, computers can optimize the process of production planning or detailing features of products such as choosing materials.

Apart from those techniques mentioned above there are other variations which are being applied by engineers.

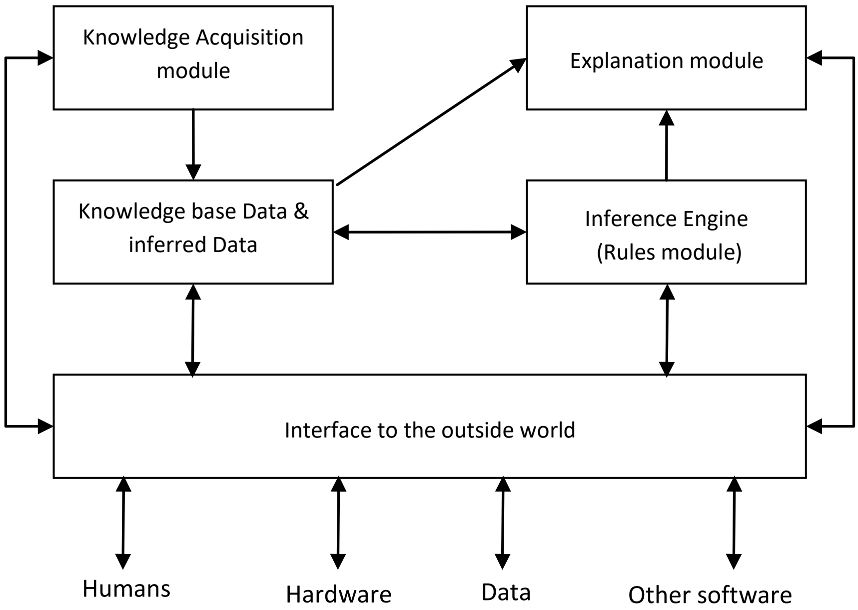


Figure 2 .39 Knowledge-based systems
Knowledge-based systems based on Andrew Bacon's model (Bacon, 2009).

In the definition of the FEM it has been said that a successful method in solving some aspects of highly complicated products or problems is to break down the product into smaller components and solve the problem in each element separately. In addition to physical and geometric issues of design we also have to consider planning problems such as manufacturing and the supply chain which would add to the complexity of the process. One of the concerns of the AI technology developers is to find out how to use a 'Decomposition' technique on products which comprise a large number of components. The other challenge is to reassemble elements to put the whole system together again without any possible defects happening during the process of re-gathering of components together after the analysis and improvement. There are several ways in using this technique in design. Decomposition can be applied either on physical components of objects or on problems, based on the chosen problem-solving techniques. There are two main approaches in the application of decomposition according to the hierarchy of design. One, as mentioned before, is to design a product and then proceeds toward details, it is called the top-down method. The second trend is to design components of objects and then assemble them to create the intended product which is known as bottom-up approach (Hinchey & Coyle, 2012).

Another AI design technique is to pre-plan several design scenarios and based on the case and contextual conditions choose a method and modify the solution to fit that certain problem. This method of 'Plan Refinement' can be used in various industries. This concept comes from Medical and Pharmaceutical procedures where doctors diagnose the sickness, choose a treatment method and based on the severity of sickness and physical condition of the patient, they modify the treatment to be effective (Gonzalez & Gomez, 2011) (Shahar, 1999).

Most design proposals are constrained by the needs, limits and creativeness of the designer. There are several factors involved in every design; each has its own fits and constraints. To design a component using a certain material it should itself be stable as well as responsive to the rest of the system. 'Constraint-based' techniques apply a series of default features on a design to define a boundary and then test elements for meeting the criteria of constraints (Yvars & Sellini, 1999).

The other technique which share similarities with the Plan Refinement method is 'Case-Based reasoning'. This approach is founded upon designing based on experiences of similar activities. To solve a problem we always search our memory for solutions to similar problems which we have used previously or try to discover answers from the similar problems solved by others. Computer-associated techniques try to simulate this activity. By referring to a data base where information about similar processes is stored and by checking the proposal against constraints, a computer can produce several alternatives for designing a product (Coyne, et al., 1990).

It has been shown in the Ohsuga model of design [chapter 2.2] that the design process can be a recurring sequence of design analysis and modification up to the point where it reaches a desired result. The process of modification can be applied to various elements of the proposal such as dimensions, components and/or structure. 'Grammatical design' is a system which finds its roots in such a model of design [Figure 2 .40]. Its way of generating design iterations is to follow a general structural instruction and rules of systematic modification which are both defined and stored in database (Brown, 1997). Based on this definition, a grammatical design database contains:

- Grammar: that creates a basic structure of the product,
- Vocabulary: all of the possible components which can participate in creation of final product.
- Modification criteria: to set regulation for possible manipulation of design based on needs and constraints and system feedbacks.

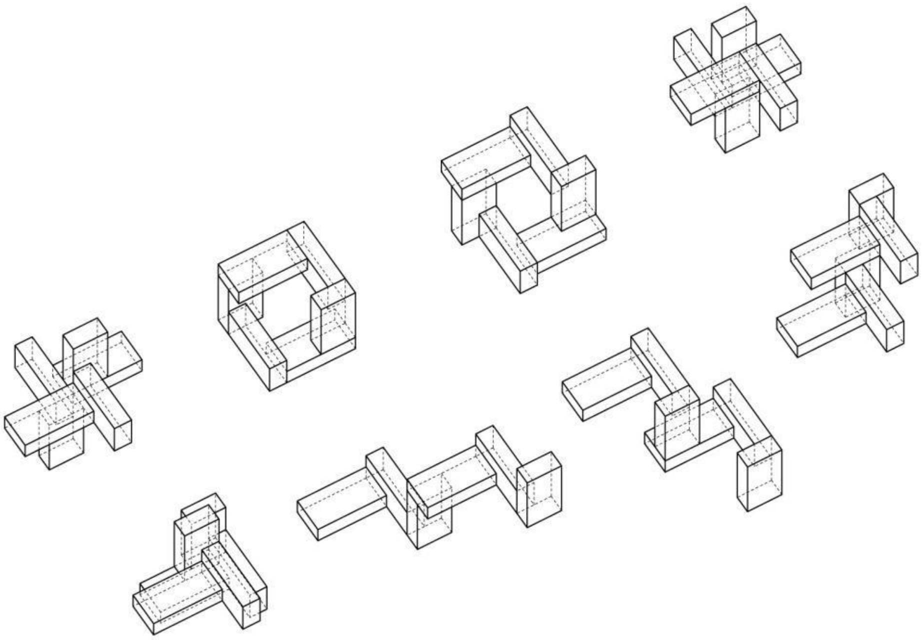


Figure 2 .40 Shape grammar
Shape grammar is a type of Grammar deign concerning the form generation. Picture (GRAPE).

Similar to linguistics, grammar in product design defines a template for the use of elements. It acts like a pattern which dictates standards and calculable procedures to design and select suitable elements existing in the 'Vocabulary' and guarantees that the result fits the boundary of instructions, carrying fixed features. Grammars can rule several aspects of a product. ‘Shape Grammar’ regulates the physical entity of design which determines selection of components and methods in which they gather together (Brown, 1997)(Stiny, 1991).

The other accepted intelligent system in production is termed knowledge-based techniques which shares many of its features with previously mentioned systems and is regarded as a collection of versatile tools. The more engineering oriented branch of this system is ‘Knowledge-Based engineering’ also known as the ‘KBE’. Such systems combine the abilities of computer aided design, rule-based techniques, object- oriented planning systems and data representation (McMahon & Browne, 1998).

Progress in a knowledge-based engineering system is based on processing an electronic knowledge model using object-oriented methods. The representational model is divided into several groups of components, each carrying a hierarchical value. Such definitions rule the links between various components considered at lower levels in order to form a bigger component at a higher level of the hierarchy (Creen & Kendal, 2007). All the information then can be attached to the product model to identify necessary processes and their details in addition to the feature of the final product. Such data can also be arranged in a manner to set up an automated fabrication process. Nowadays, KBE has been developed as a design tool which works in hands-off areas of design with minimum human impact on the design process (Akerkar, 2009).

Although KBE is a versatile tool in design its specialties are more apparent where there are a variety of final outputs based on one core design planning procedure. Basically the application of KBE is to run an automated process of repetitious rulebased design work. The direct influence of such a system on the whole process of design and production. The overall intent is to remove tedious and time consuming manual routines in order to give more of the overall resource to more productive parts of the organisation – such as the design stage (Ruschitzka, et al., 2010).

2.5.3. Parametric design

When designing various types of products, sometimes it is a case of making objects owning many similar groups of characteristics but with slightly different volumetric shapes or objects with related geometries but at different scales or dimensions. In these cases, parametric design is a useful approach, where we can set rules and alter other features to gain different but desirable results [Figure 2 .41].

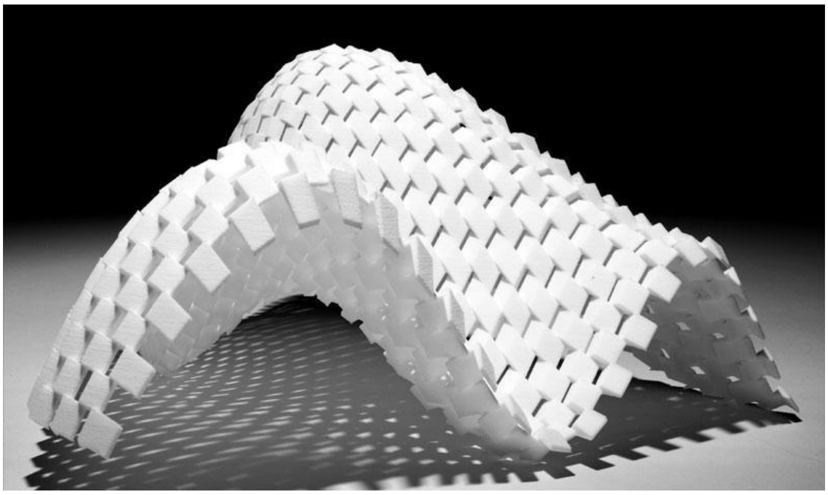


Figure 2 .41 Parametric Design
Picture (Rossi, 2007).

Undoubtedly, in order to design a duplication of a certain group of objects it is always possible to define geometry rules by computer codes in order to conduct an automatic design process; yet, any changes in geometry or standards must submit the project into a tedious process of repetitive change of computer codes which needs the constant input of highly experienced software experts to reprogram and test those commands with which the geometry should be designed. Such trends can lead to success only if we work with very well defined objects, have plenty of time to reorganize the system and have the required staffs that are well integrated into the source design so as to be able to review command codes. To avoid the complication of the process some new systems of parametric designs have been promoted which allow adjustments and changes throughout the design process. Instead of creating and recreating design models users with much less software skills than what were needed before can modify and recycle design models.

Many types of new parametric design methods have been introduced in recent years. These systems enable us to define objects either by physical features or variables and parameters. This approach allows users to change physical features of the design simply and rapidly by changing the value of main parameters (Roller, 1991).

2.5.4. Models and features

One of the popular design abilities in the majority of industries is to form a volumetric shape of an object or component and to modify it toward the desired results. Products with a high level of complexity also need applications with higher geometric reasoning capabilities. On the other hand, not many of the existing Artificial Intelligence computer applications go any further than geometry reasoning or being programmed to produce geometrically limited objects.

For an architect or product designer it may only take a superficial study of a model to understand what the dots, lines, shapes and symbols represent. This way they communicate with the model maker no matter who it is. An expert can recognise all the technical properties of designs through reading the symbols and annotations. The problem here is that this form of information is only descriptive and does not add any practical characteristics to the product models. These engineering characteristics are known as features and most of the older computer aided design systems are also incapable of adding any real life engineering features to objects or components and ultimately product models.

Initially what was called as the features of components was directly related to geometry of them. By today's definition, feature of a part could be its role in structure, mechanism, etc. Nowadays, not only geometry but also other engineering information and production strategies are regarded as features. Fabrication and machining details of components, material and basically any characteristics of products are forming features of products. "*A feature is any perceived geometric or* *functional element or property of an object useful in understanding the function, behaviour or performance of that object*" (Brown, et al., 1992).

It has been claimed before that CAD models can carry features of components. The mechanism which defines these features in a CAD model is known as feature recognition. There are three major approaches in this area. Firstly, syntactic pattern technique which uses 2D elements representation to define a geometric pattern, secondly rule-based system which uses series of rules to define features, and thirdly, graph-based applications, which uses graphs to produce models (Shah & Mantyla, 1995).

Among all of the feature-based techniques, feature-based design is probably one of the most attractive yet not the most comprehensively developed. The concept behind this method is to make models from scratch, using components with predefined features [Figure 2 .42].

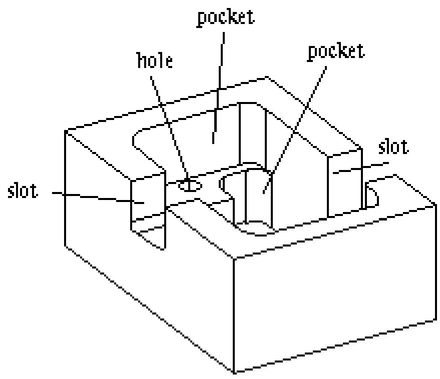


Figure 2 .42 Feature-based design
Design of a mould by Features. Picture(Salomons).

In this system there are many approaches to design. As an example we can consider the 'destructive' process [Figure 2 .43]. It can be said that the users of this method basically have the sculptors' approach of taking the raw material (wood, stone, clay and so on) and subtracting pieces from it to reach the intended shape. Such a process is trivial to automate with a computer issuing a hierarchy of commands where 'features' are interpreted as a set commands which invoke machining operations to remove parts of the block of raw material and form new geometries. The process of design in this system is unlike what designers usually do. In fact designers need to know and understand the geometry of final products before starting to work on models. The other negative point is that designers need to have a detailed knowledge about the intricacies of the machining and fabrication processes which is not always the case. A CAD application may supply some preprogrammed features [templates] or offer to designers the capability of defining new features (Shah & Mantyla, 1995).

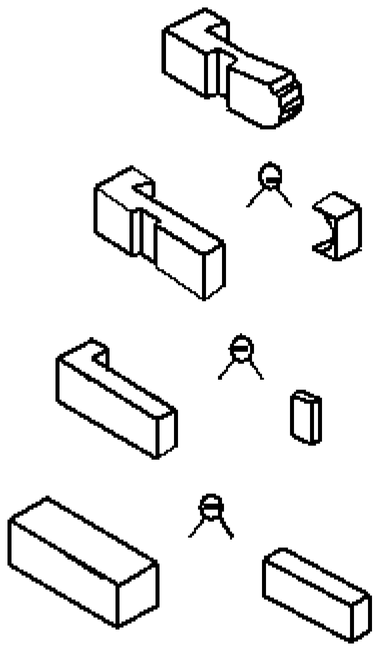


Figure 2 .43 Feature based
A schematic example of the Feature-based production showing three stages of a Destructive process. Picture (Parry & Bowyer, 1993).

In addition to that mentioned above, Feature-based techniques offer many more automated activities to their users; some of them are as below:

- Creation of projects' FEM
- Process planning for CNC machines
- Casting and forming process planning
- assembly planning

What can be more or less foreseen is that the number of these functions will grow gradually as ongoing research and development expands the domain of featurebased techniques' in design projects (McMahon & Browne, 1998).

Part three: Production design and manufacturing

2.6. Design and manufacturing hand in hand

2.6.1. Introduction

Throughout this chapter we are on a short journey from the initial design to the fabrication of products. The journey begins with investigating the emergence of traditional methods of design and fabrication and the links between them and identifies the obstacles of those old techniques [although many of those techniques are still used all around the world but in comparison with emerging systems they are considered rather dated] to create a strong relationship between design and manufacturing. Focusing more on process design instead of the product itself, is possible to show how concurrent engineering can increase efficiency and productivity of systems as well as reducing miscommunication and errors while keeping repetitive processes to the minimum. The following discussion focuses more on the strategies which can be applied by designers to determine the production type, process and flexibility of such methods.

In fact the intention of any engineering design project is to satisfy demands; consequently all the efforts of the engineers in all design and production projects are focused on finding fulfilling solutions for those needs by making the most appropriate and efficient use of resources. An engineered product is the result of a design being somehow turned into an artefact by connecting designers and manufacturers.

For every type of product there is a unique timeline which defines the product lifecycle; but, there are some key steps in each timeline which are related to the formation and realisation of products which are the same for most artefacts. These can be seen in the Figure 2 .44.

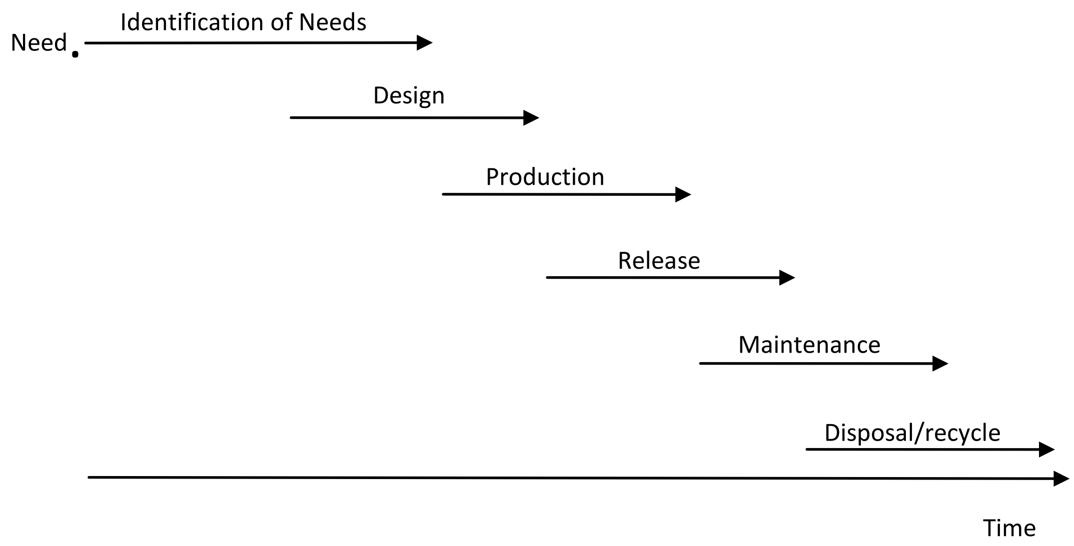


Figure 2 .44 Product lifecycle timeline
Extracted from (Tunstall, 2006).

Not long ago, the process of design and fabrication used to be regarded as two separate procedures and in order to bring them together and make the production more efficient and accurate, process and production planning appeared more as lateral activities [and not a main activity] supporting the main stages which would be Design and Fabrication [Figure 2 .45]. The summary of such a process is basically to complete the design activity [applying any appropriate design model], and then to translate those proposals so as to be useful and understandable in factories. Thereafter there is a need to plan for production strategies and finally to apply those plans to the task of fabricating products. By reviewing conventional systems it is noticeable that not only are design and planning influenced by all the complications caused by applying totally discrete stages of work but also such a slow and long process can distance the production line from the market and consumers. Due to time consuming processes and the inherent inflexibility of the production line and associated machinery, coupled with a changing market, may lead to producers manufacturing artefacts in a constant fashion while they are not sure about the market expectations and consequently the profitability of their product. Companies employing inflexible systems are mostly incapable of competing with other companies since flexible systems can enable the design and release of new products in response to updated market reports.

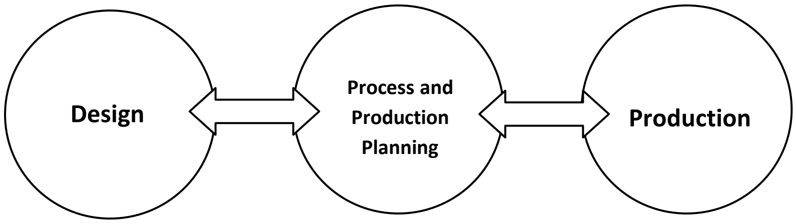


Figure 2 .45 Design-fabrication
Design and Fabrication link in a traditional system.

A large number of popular companies determine their production strategies based on constant improvement and try release new versions of their products at least once every few months. Sometimes only a few weeks after release they have to redesign their products and make amendments to sustain their presence in the marketplace. This is the reality of today's design, production and engineering business. Tight competition between companies and fast growing technology and demand have made for a more rapid pace of change, therefore setting up an inflexible and fixed production facility dedicated to the fabrication of one certain product is becoming exponentially disadvantageous (McMahon & Browne, 1998). As has been mentioned before, nowadays, the separation of the two phases of design and manufacturing within a project can be disastrous. Designers being unaware of fabrication line constraints or capabilities can sometimes result in poor proposals which lead to severe problems in the factory. Apart from that, representational models carrying design proposals can be deceptive or not capable of containing enough production data so that the fabrication team may be misdirected about the reason of some features of the design proposals. On the other hand there might not be any valid feedback from the production line to the designers about problem areas. Indeed miscommunication can happen in various directions and only a direct link between teams may help avoid unintended consequences.

It has been mentioned previously that the most dominant concept in many traditional models of design is to design, evaluate, develop and redesign [and reevaluate]. Such a circle of actions in a high level of proficiency and detailed consideration may lead to both cost and material waste reduction in the production line. But a repetitive process is also both time and money consuming in other ways such as when in the design phase companies need to spend time and money on recurring procedures and recruit a workforce to redesign and readjust design proposals based on evaluation results.

2.6.2. Modern fabrication engineering

The modern world has created a high level of demand amongst users which has changed the concept of manufacturing with minimum defect to a zero defect production with no error tolerance using lean production techniques (Black, 2008). It requires a very accurate study and in depth market research to map users' exact needs. Currently, product design and planning must be very well organized because in such a competitive environment developing products with higher quality than even that of a prospective user's anticipated needs means more time and money and could be considered as a loss for companies. In a modern flow of work, the quality of final products is definitely dependent on the output of all members of the project and not just on one certain production team. That approach to the quality of products brings up the term 'total quality' [Figure 2 .46] that is integrated with all over the whole production process and involves all groups (Peratec, 1994).

In a total quality organization it is vital to regard each department and process as a small subsystem working within a larger system. A system works optimally based on defined rules, dedicated to that unique system. A 'fabrication system' consists of processes which produce artefacts, as optimal as they have been designed; such artefacts are also considered as systems which have to work as they have been designed to uniquely fulfil the targeted need. In these systems stagnancy equals corruption and in order to be able to cope with changes and respond to new circumstances they need to have a margin for 'steady development'. Instead of trying to design an ultimately perfect product [which is not possible due to rapid changes in technology and expectancy] it is more practical to enable modification and persistent development in a system (Peratec, 1994).

Figure 2 .46 Total Quality Management
Elements of a Total Quality Management based system. Extracted from (Satpathy, 2008).

It has already been said that the segregation of the design and fabrication phase undoubtedly reduces the quality of products and that design refinement in order to meet manufacturing constraints needs to be delayed until the end of the design process. To solve this problem it is necessary to establish a high level of communication and collaboration between all departments as well as concurrent development of the product design and production planning. Simultaneous engineering and planning regards all stages of a process as concurrent procedures which are developed at the same time with due consideration of each stages influence on the quality of other stages of progress. Undoubtedly the success of a simultaneous trend is highly dependent on teams with certain specialties, each carrying out predetermined jobs dealing with some aspect of the project while cooperating with other teams (Prasad, 1997).

Conventionally, the life cycle of a product used to start in one of the companies' departments and as it was developing toward fabrication it got passed between various departments. In those kinds of companies their activities were mostly systematized as artefact engineering and fabrication engineering. Now, modern companies have applied a concurrent approach in their work flow comprising a group of multidisciplinary experts, gathered in the product engineering team to navigate and monitor products' life cycle from initiation to termination (Nevins & Whitney, 1989).

Ultimately there are strategies which are taken in order to apply systematic modifications. All of the conceptual and systematic changes in modern approaches require some innovative methods of design and production to evolve the process. 'Quality engineering' applies these methods throughout all operations of a project. In fact the quality engineering concept is an organized group of techniques which directs engineering endeavours in the direction of the fulfilment of all initial needs as well as considering enough of a margin to discover probable defects and refinement.

Computers can also play a prominent role in this process of systematic change. Computer aided technologies such as computer-aided design [CAD] and computeraided manufacturing [CAM] are becoming the inseparable parts of the modern organization of the collaborative team efforts which demands information sharing and automated procedures. A CAPP [computer-aided process planning] technique can use computers to help extract data, are capable of operating CNC machines or assist in the planning of fabrication activities. CAPM or computer-aided production management equip users with the ability to monitor, assess and modify the fabrication process. In order to do that, CAPM applications need to be fed by fabrication data and the quantity survey of materials. The use of computer-aided technologies and automated procedures which all link to a core information resource is usually named as a computer-integrated manufacturing [CIM] system [Figure 2 .47] (Kalpakjian & Schmid, 2006).

In fact 'CIM' could be regarded as a system in which all production related functions are connected through a digital organization controlled by computers based on the commands given by system designers in order to keep them all in step. The ultimate purpose is to apply 'Information and Communication Technologies' also known as 'ICT' to prevent miscommunication and to facilitate concurrent systems offering efficient procedures. The main area of CIM's focus would be to organize the supply chain by synchronization of the manufacturing progress with several providers, connecting the design data with the manufacturing line and controlling the flow of work along the production line (Kalpakjian & Schmid, 2006).

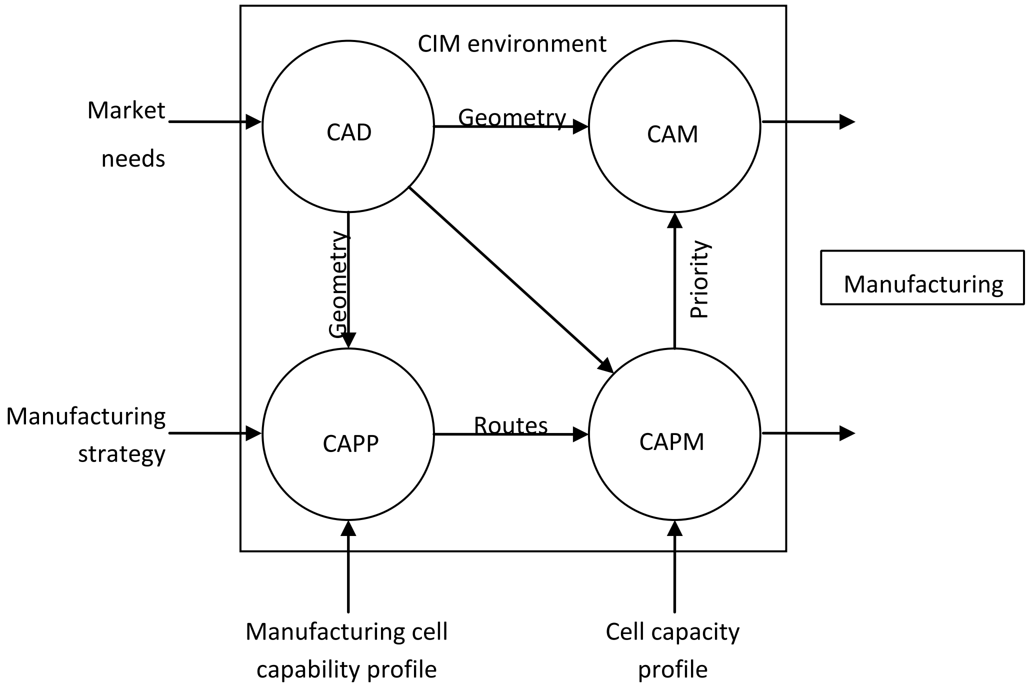


Figure 2 .47 Computer Integrat ed Manufacturing
Flow of information in CIM. Diagram (Lucas Engineering and Systems, 1988).

In order to expand the capabilities of computer aided technologies many research projects have been directed toward the exploration of File to Factory technology which in fact automates the collaborative work of designers and manufacturers. It is noticeable that currently there is much misuse of this branch of technology in that it is being employed to just supplement traditional methods or to automate an old style of project organisation. Today a product team is expected to work in a system where product and/or process investigation constantly and repeatedly tests the design to check it against the constraints of manufacturing and so creates an optimised production plan based on the fabrication method aligned to the expected end product. Figure 2 .48 demonstrates the link which is made between CAD and CAM by computer-aided process planning [CAPP] (Rao, et al., 1993).

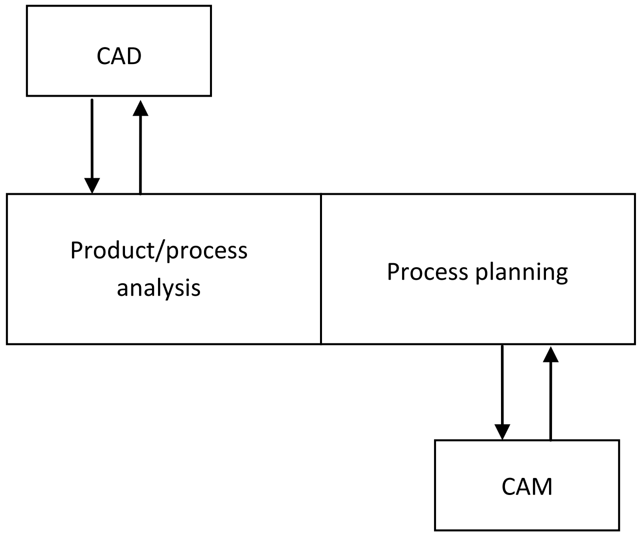


Figure 2 .48 Computer aided process planning

Schematic figure showing circulation of data in a CAPP system.

2.6.3. Group Technology

One way to optimize projects is to categorize components of products based on their properties. This categorization can be based on any feature which suits the interest of the project such as size, colour, material or even fabrication operations. Such a breakdown of the product has become recognised as a production method called 'Group technology' or 'GT'. GT is a technique for identifying and bringing together related or similar components in a production process in order to take advantage of their similarities, by making use of, for example, the consequent benefits of 'flow-production methods' [Figure 2 .49].

The main task of GT is to create product layouts and thus streamline the fabrication process. This way production and production planning of families of parts can be assigned to a certain group of engineers and technicians. In addition the configuration of material supply would become much easier and the time taken to relocate materials between machines and sites as well as any required device installation and adjustment times are reduced dramatically.

Other uses of families of components are when engineers design a process for the production of a component. There is the opportunity to inherit a process plan from other components of the same family. In the main, some minor modifications may finalize the production plan for new parts.

GT groups parts based on their similar geometry, physical features and process of fabrication. Engineers now have some standard guidelines for component categorization. These standards may vary in different countries or even from one company to another based on their needs and organization (Syresh & Kay, 1998).

Figure 2 .49 Group technology

By grouping the components of products in part families machining and other fabrication activities and planning are becoming more efficient. The picture shows bronze machined parts carrying similar features grouped in families. Each family may pass through almost the same manufacturing and planning stages.

Picture (J-Tech Sourcing, 2013).

2.6.4. System organization

The trend towards the analysis and categorisation of systems and environments which tends to group them through recognition of their constitutive elements [reductionism] has aroused controversies about their accuracy since individual parts may not work well when gathered in one product. Many specialists believe in a 'systems' approach in which systems are regarded by a plenary view rather than being analyzed or developed based on analysis or development of their individual components. One of the advantages of this approach is that users can reversibly break large systems into smaller systems. Another feature of the systems make up is that one system can be considered in a network with other systems. For instance we can always see the link between the production system and the system of the supply chain. As has been mentioned in this chapter so far, systematic and plenary views are an essential component of many production projects. Therefore we need to develop all subsystems [as larger systems have been broke into smaller systems] simultaneously to have a better understanding about needs, limits and each subsystem's impact on the progress of others (Checkland, 1981).

2.6.5. Simultaneous organizations

By new standards which get tighter day by day, prosperous projects can be regarded as those in which experts from various fields feed knowledge into the system from the inception to the completion of projects. It is also a time saver in the engineering stage due to the elimination of the repetitive cycle of gradual development and this type of the economy of time can happen over all the various stages and procedures. In fact by using 'Simultaneous Engineering' the fabrication process and all of the related activities may happen almost at the same time as the design operations.

With companies moving towards the adaption of simultaneous system they can become divorced from the traditional way of dividing product and fabrication engineering. The two groups of activities were traditionally separated distinctively and sometimes were even managed by separate persons; while the modern system is more team and organization oriented and tends to develop the project in one unified group, the project team.

There can be some variety of views in regard to the team oriented flow of work. In companies, they can form groups based on the families of their products. An example can be the construction companies. They may have teams which work on the construction of roads, harbours, marine structures or/and bridge construction depending on the domain of their work. In team-based organizations it is preferable at any stage to have an appropriate group of experts with a variety of specialties to work together. In complicated projects or in companies that produce many products in order to make processes more productive it is an option to create a matrix of the organization. Such a matrix serves to divide experts based on their area of expertise into different departments and then based on the needs of any project then defines the quality of each department's involvement in various stages of production. A matrix organization has been demonstrated in Figure 2 .50. This kind of matrix or table of workforce allocation can also define a standard for a companies' hierarchy of procedure and highlights departments involved in the production of artefacts of the same family.

Apart from all of these organizations, we should always keep in mind that despite all the efforts to standardize the production process every single type of product needs an optimal organisational strategy to realise the feasibility of the operation. Every guideline has its own limits and constraints. Team oriented organizations may have the advantage of concentrating all the focus of different departments on the products throughout a products' lifecycle but offers a limited capacity for the exchange of expertise between the different departments or product teams whereas, those previously defined in this document and employing a more traditional system may provide a greater exchange of expertise (Kerzner, 2001).

Department	Project / Staff	X	Y	Z
	Project leader			
	Project engineer			
Design	Designers			
	Draftsmen			
Development	Development eng			
	Technicians			
Manufacture	Manufacture eng			

Figure 2 .50 Matrix organization

An example showing 'Matrix organization'. Table Extracted (Kerzner, 2001).

2.6.6. Design for manufacturing and design for assembly

Traditionally over 70% of a project's budget is fixed by the designers (Andreasen, 1983); whereas nowadays designers are gradually becoming more distant from the fundamental procedures of production and fabrication due to the growing specialism of their own work and the fast growing complexity of novel fabrication techniques, new materials and machining tools. This deficiency has raised the request for technologies that help designers toward 'DFM' or 'Design for Manufacture'**.**

DFM can be regarded as a descendant of a traditional means of creating successful projects but harnessed in a more modern way by seeking the creation of a series of multidisciplinary design standards defining limits for the designer to more or less guarantee the feasibility of project in regard to the existing fabrication capabilities. In the same way as in any other field, DFM has benefited from computers in many ways. There are automated mechanisms that can analyze design proposals and evaluate their fabrication feasibility based on pre-defined boundaries. They can also simultaneously feedback some guidelines for the improvement of the design. One of the techniques is called the 'DFA' or 'Design for Assembly' [Figure 2 .51]. DFA is becoming one of the key branches of the DFM system, playing an important role in many projects. Since the assembly stage is potentially the most labour intensive stage of production and the greater the workforce the more expenditure on labour, hence assembly can become the bottleneck for projects. Although DFM defines design limits in almost any field it is vital for a designer to have a concrete knowledge in regard to the design limits and does not wholly rely on automated evaluation and correction. It is common that some of the DFM standards may not respond to some project intentions or other classes of constraints. It is not a surprise that in every system there may be some ambiguities that exist, especially in pioneering projects and organizations which do not have any prior examples to follow.

To sum up with, some basic concepts of the DFM techniques can be named as follows:

- Benefit from the reduction in the size of projects ○ To use similar components in not one but as many as possible artefacts
    - Reduce the number of components as it demands less engineering work and simplifies the assemblage and reparation.
- Regulate the process but do not limit creativity ○ Apply components with previously proven success ○ Use a diversity of parts from one family of components
- Apply straightforward techniques ○ Apply methods with previously proven success
    - Apply expensive methods only if they are essential for execution of project. ○ Do not apply highly complicated geometries and joints

As posterity of the design for manufacture, design for assembly also can automatically execute procedures as follows:

- Identification of influential factors on assembly
- Regulate and abbreviate assemblage procedures
- Identification of the impacts of assembly process on product design (Molloy, et al., 1998).

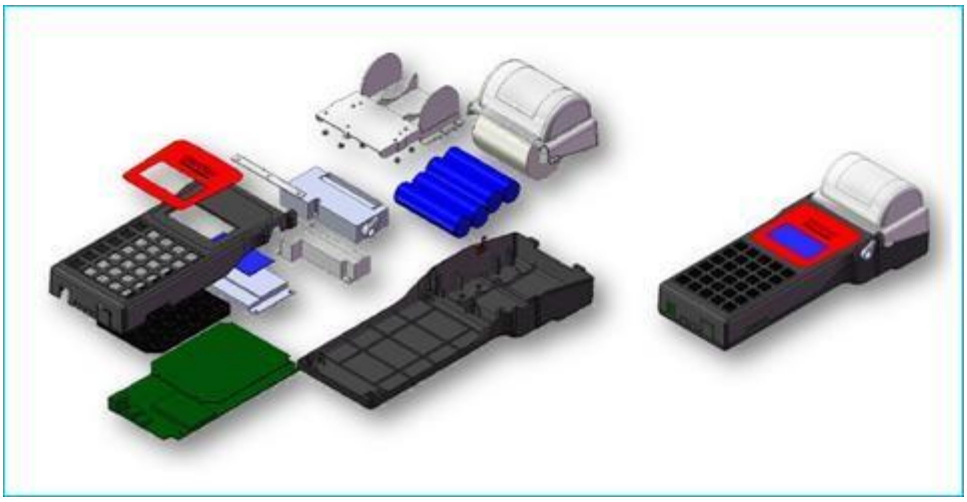


Figure 2 .51 Design for assembly

Design For Assembly. A demonstration of the assembly quality showing the hierarchy of actions and location of parts in production of a card machine. Picture (Collabera).

2.6.7. Approaches to process design

In a products' life cycle, the act of process planning is attributed to the translation of design geometry, joints and other features to commands and details which describe the timeline and hierarchy of procedures, machining and finish guidelines and basically serves to direct the fabrication phase. Therefore the process planning has righteously become an essential element in the integration of modern design and production.

It is important to know that in most cases there is always more than just one available plan in the production of artefacts. The most appropriate general plan would be chosen by the production strategist depending on a large variety of factors and details of any procedure which also may differ from one product to another. For example the volumetric features of a design, the size, and number of components or required products, etc. are totally influential on process planning. Certain types of materials may need special machines, tools and techniques for shaping and finishing, or if the number of products is more than one sometimes planners may choose, for instance, a casting process over CNC techniques. Planners also consider the accessibility of tools and cost benefits (Chang, 1990). To match the requirements of a modern production project there should be a systematic approach to the plan of a production process.

There are many different ways in the systematic approach to production process design; one of the popular examples is known as 'GENPLAN'. This approach is a thorough and well defined structure introduced a systematic approach toward the process design (Gindy, et al., 1993). This system defines the form of dealing with geometry, objects and components, joints and assembly, using available fabrication methods and devices and finally designing a suitable production process. GENPLAN then categorizes this information into two major groups called 'absolute knowledge' and 'constrained knowledge'. The first contains geometrical and volumetric features and the latter consists of end product physical appearance and dimensional features. The categorized data then forms the basis of a three-step process. The processes start initially with checking the feasibility of design proposal.

Afterwards it is time to select the manufacturing system which meets the requirements of the project in the best possible way. The final phase is to design a productive, detailed and optimized process based on all previously gathered information (Gindy, 1992) (Gindy, et al., 1993).

Previously the conventional way of process planning was to perform all the work manually and by hand, where the quality of the result was totally dependent on the personal knowledge and abilities of every individual involved in the process. In fact process planners had to analyse the geometry and prepare technical drawings for the fabricators' use, define all the machining work and the hierarchical order of operations all based on the nature of these systems ultimately the resulting plans may inherit some human errors and may not benefit from the best organizational order as the limits of the human conceptual capabilities may be limited when concurrently considering many parameters in a single process. Certainly for most of the time it is the case that plans may not follow the same standard. Clearly computers did not let the same flow to continue and revolutionized the traditional methods.

What is known as CAPP or computer aided process planning presents a vision of an automated process which reduces the process time and provides accurate plans based on standards and rules which potentially can increase the productivity of the process. This automation can run through all the required steps if users can establish the CAD, CAPP and CAM link. This connection is the key element to automate the data transfer between all designs and manufacture phases in order to create a unified process (Gindy, 1992) (Gindy, et al., 1993).

In order to briefly summarise chapter 2.6, it should be said that in the current climate, where the market is demanding high quantities and qualities of products, rivals in the production industry are steering all of their efforts towards a single aim which would be to own a bigger share of the market. Therefore it is essential that producers and service providers increase the quality of their products while delivering a high volume of products and services while still decreasing operating costs. A total quality system needs to run these aspects of the organisational work.

This system needs to involve all members of the projects in all stages of production process thus an ICT system is necessary to manage the communication and flow of information amongst project members. This communication system can unify the product design, process design and manufacturing together [Figure 2 .47 Computer Integrated Manufacturing] and allow concurrent progress [e.g. product design and production design could be done simultaneously] which will increase productivity, efficiency, accuracy and profitability of projects.

2.7. Fabrication organization and machining planning

2.7.1. Introduction

This chapter seeks to establish the role of machinery and machining process in the development of design and process planning. Therefore it initially demonstrates 'NC' technology and visits the required and existing machinery to realise the concepts before progressing through the various approaches to planning the process using this technology. In the following sections some of the data preparation methods for the purpose of fabrication such as 'Automatically Programmed Tools' and 'Cutter Location Data File' are investigated. By involving computer-aided technology in the manufacturing process, the following chapter defines the capabilities of 'CADCAM' in product engineering and the fabrication of complicated geometries. Furthermore 'Rapid Prototyping', 'Robotics' and their contribution to process and assembly techniques will be illustrated.

2.7.2. Numeric Control

The technology commonly referred to as NC or 'Numerical Control' is a technique to automatically control machinery in order to fabricate artefacts. The commands which are fed to machines are usually stored in the form of codes which have been saved on various types of media. In fact these codes replace the input from the traditional mechanical and manual controls of machines such as wheels. The first signs of the implementation of NC date back to 1940s when Parsons encoded machining commands, which were then represented on punched cards, to control the fabrication of curved objects such as aircraft components (Smil, 2006). After many years of gradual progression in the capabilities of NC and improvements in regard to accuracy, speed and the increasing number of complicated geometries which can be made using this technique, NC has become the key fabrication factor in most advanced manufacturing industries. Nowadays it is possible to make components by subtracting materials off billets or to use lasers, water jets or plasma cutters to cut sheets and create parts or even assemble components of an electronic printed circuit board all automatically [Figure 2 .52]. In fact NC has radically changed the production of singular and unique components. Also what we see for example in car plants as robotic hands which assemble automobile parts are actually numerically controlled machines which work based on inputs fed to them by coded commands.

Figure 2 .52 Numeric control
NC machines can cheaply mill foam moulds for production of precast concrete panels in a short period of time. Picture (GBM, 2010).

The currently available NC devices are the result of more than 50 years of consistent development. Such machines commonly consist of a controller also known as 'MCU' or the 'Machine Control Unit' which plays the role of the brain for the machine. This part of the machine is responsible for the retrieval of saved data and then uses this to control the 'actuation devices' which perform machining on work pieces. Initially the media for the transfer of commands to machines were punched cards and then magnetic tapes appeared which were capable of storing large amount of data. And now, machines can receive information from computers even from an unlimited distance. In a process conducted by a MCU, feedback from the machine, which might be quantitative and/or qualitative loops, is essential to keep the process on track. This feedback is detected by sensors. Based on the shape of the intended products the MCU controls the movements of the cutter and/or the billet holder. Due to the versatility of machines, they can now move in various directions from one to five-axis [Figure 2 .53] (Jain & Chitale, 2010).

Figure 2 .53 A five-axis router Picture
(5 Axis CNC Routers, 2008).

There are different types of movements which can be defined to machines. Some machines may only be capable of limited kinds of movements. The most basic movement is ‘point to point’. In a pre-defined plan, the machine moves from one point to another and makes certain changes to the work piece. As an example, an automated drill which should make holes in certain places of a sheet can be programmed for point-to-point motion.

A straight cut is the second most fundamental type of motion where machines can cut or move only on one straight line and at a given speed. This type of movements creates many limits and constraints for the production line. On the other hand as an example of a more sophisticated technique, contouring by numerical control mixes the point-to-point motion and straight cut together to perform accurate motion on a flat surface and in two axes. Each curve is defined by many straight lines in this system. Apart from controlling the cutter's motion, the MCU can control the speed of any process, position of the work piece via clamps and chucks as well as controlling cooling systems and many other operations which are involved in the machining process of certain objects (Jain & Chitale, 2010).

Until the 1970s, what we can find as fabrication control devices was generally mechanical. The machine control units basically had no capability for saving and supplying successive commands to a device and could only manage them sequentially. In addition the abilities of the control units were limited regarding the variety of commands that they could handle. It was only in the late 20th century that manufacturing control was revolutionized due to the integration of computers in the process. Computer Numerical Control [CNC] has equipped control systems with a storage unit where successive commands could be stored and analyzed based on the feedback received from the production and machining line. Consequently the overall speed rises and changes of process can be executed relatively easier and faster. Nowadays and with the help of digital technology highly complicated commands and operations can be organized with much greater accuracy. The new generation of CNC machines have digital input and output links which are compatible with regular personal computers; this makes the working progress much easier and faster. Some CNC tools even provide graphical representation of the real time condition of the work piece and the process being performed, this serves to create a better user interface with the system operators thereby facilitating assessment and decision-making activities (Bedworth, et al., 1991) (Kalpakjian & Schmid, 2006).

Not only have the fabrication control systems been transformed by the progress of technological development, but also machinery and fabrication operations have been improved dramatically due to the advance of computer science and robotics. Instead of being dedicated to certain materials, forms, production operations or products, machines are turning into versatile tools which operate on many different material families and are capable of the production of numerous product families.

This equals a reduced installation and adjustment time as well as providing for faster modifications and ultimately the capability of producing a wider range of products. The major advances provided by current technologies are (Schodek & Bechthold, 2005):

- Instrument magazines which allow machines to be equipped by necessary tools fitting the desired job and the required level of precision. Depending on the machine type, they can have magazines storing tens of tools in different shapes and sizes.
- Product and raw material magazines which allow an automated process of feeding raw material to machines and store machined objects, ready for the next step.
- Multi operational machines capable of executing two or more different types of jobs on the work piece at the same time

2.7.3. Data exchange strategies

As has been seen previously, whether being performed sequentially or simultaneously, there is always a plan and a planning activity to link design and manufacturing together. The operational plan used to fabricate objects in a numeric control system is known as the 'part program'. Either being in a fabrication team or in a product team, part programming is considered as the regeneration of geometric features of design in the form of product specifications which proceeds to the generation of coded machinery commands. The traditional view on this operation would be to expect the job to be done manually by planners going through the technical drawings and calculating the machining operation details before going on to coding forms and creating codes which then could be punched on cards (Seames, 2002).

Currently through all the improvements of recent years, part programming for fairly straightforward geometries are sometimes done manually. Input and output devices of NC controllers have made part planning and modification extremely simple. There is always the advantage of standardized procedures and established process samples. Nonetheless highly sophisticated geometries have always been challenging and perhaps even impossible for part programmers to program manually. Computer assisted and recently even fully computer integrated programming systems have widened the circle of producible artefacts while demanding less time and carrying less errors and stepping toward zero defect production. As has been demonstrated in Figure 2 .54 one group of these improvements is related to computer applications that allow users to manually plan and the other group are those applications that interpret fabrication data straight from CAD models (McMahon & Browne, 1998).

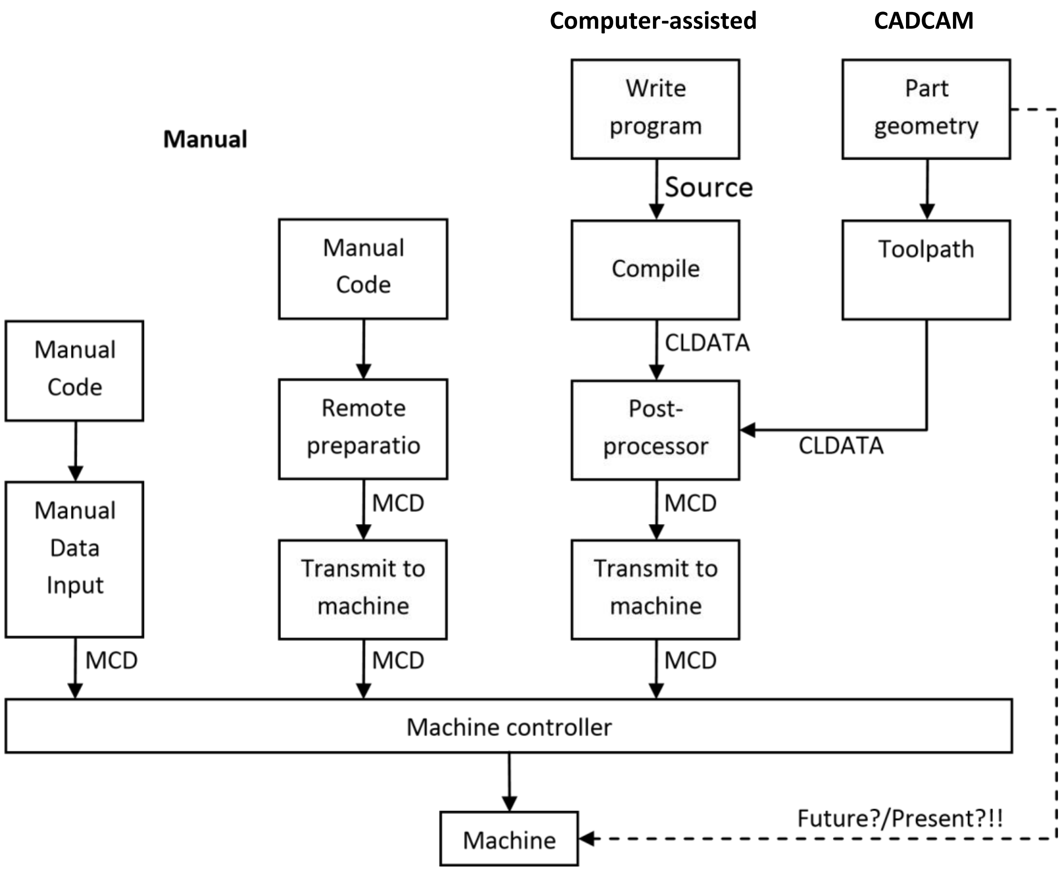


Figure 2 .54 Part programming

Alternative routes for part programming. It is demonstrated that NC machines now can be programmed manually or by computer applications. It also can be seen that the most basic way is to do it manually; basically to translate the design to sequential machining processes manually and then transfer them to the machine manually [primarily using wheels or levers]. On the other hand in the most modern way all the machining data could be extracted from the digital model by directly connecting the computer to the CNC machines. Diagram (McMahon & Browne, 1998).

Part programs necessarily have to adhere to a tight set of standards. The NC standards and computer applications and programming software that are being used currently are mostly considered outdated since they all have been established some years ago and factories using them are mostly not willing to change machines, software and to train their staff repeatedly as these procedures are time and cost consuming. Generally machines receive packages of data in which they carry commands and necessary information for identification, speed and machining routes known as 'MCD' or 'Machine Control Data'. Each family of commands are conventionally recognized be certain letters.

- Series number (recognized by letter N) to refer to a certain data pack.
- Preparative actions (recognized by letter G) are of a high level of importance since they inform the MCU of operations that will happen. Using it, machines do initial preparations to perform planned action.
- Coordinate data (recognized by X,Y,Z,A or B) to locate cutters and work piece holders
- Cutter feed tempo (recognized by letter f)
- Movement velocity controller(recognized by letter s)
- Tool selection data (recognized by letter t)
- Diverse control (recognized by letter M) data mostly used to control devices or systems of fabrication machines.

It is necessary to indicate the place where a data pack is finished by adding EOB (End Of Block). Here we can see an example of command data package:

N005 G02 X40. Y80.130 Z160. F.80 S2500 eob

(Seames, 2002)

Investigating manual processes can be a good starting point in this topic. Commonly, manual jobs of any type are prone to receive the least possible assistance from machines and digital technologies and rely mostly on manual capabilities. In the same way as any other man-driven precision production procedure it is complicated and needs a high level of expertise and experience and is largely prone to mistakes; especially when bulk material removal is the intent and due to the complexity of detailing machining paths. Nevertheless there are two groups of assistive functions that reduce the hardship of manual processes for programmers.

- 'Canned cycles' which comprise repetitive routine activities and can be used in many different production processes and at most need minor adjustments to fit various operations.
- 'Macros' or 'Subroutine' are the second groups formed by repetitive processes throughout certain machining process and eliminate separate design of each repeated process (Seames, 2002).

If we want to take a step forward and replace manual programming by a more advanced method, it would be to consider computer programming applications that allowed programmers to define the geometry of objects and machinery processes in computer languages. Computers then can do the calculations and translate the programs and connect them to the machinery by making command packages. While today we can expect to see fully automated production process planning and manufacturing in highly sophisticated fabrication systems, there are production lines in many factories in which parts of the process are performed automatically but where much of the operational information such as dimensions, positions of the work piece and cutting tools, motions, speed and tool path must be measured, calculated and fed to the system manually. Programmers who use computer programs to plan machining processes usually follow these steps (where, as previously mentioned, any of these stages could be a part of an automated system or be performed manually):

- To define volumetric features of objects, movement of tools, inputs, velocity
- Encode all the gathered information based on the computer program and type of fabrication machines being used.
- Preparation of 'CLDATA' or the 'cutter location data file' which is basically series of cutter motions and other machine movements and controls.
- Adjusting CLDATA to create MCD for certain tool which is going to be used to feed MCD to MCU and run operational analysis (Seames, 2002).

Nonetheless, the ultimate method of part programming which is currently being used is an enclosed feature of the linkage of CAD and CAM, which allows the part programmes to be extracted straight from CAD models. This operation can be performed by directly transferring models to the computer-Aided Manufacturing application or by utilising numerical control applications existing in CADCAM software. No need for human interference in the process of encoding physical features of parts means the elimination of manual procedural mistakes. Furthermore such applications facilitate programming by illustrating the end product of any machining process and also enable users to modify the plan as required by the intended product. It is also possible to preview the tool motions and machining paths. Furthermore, part programming for complex geometries that were not possible using older techniques also become feasible by utilising automated techniques. This way, new forms could be devised and used in innovative product design.

Generally the CADCAM oriented part programming starts with the recognition of critical features of objects which will affect machining. Geometries may require to be modified to fit better with the machinery and their motion constraints. In the next step it is essential to identify the tools' features. Then the hierarchy of operations and cutter path should be programmed. All of these processes can be simulated digitally and any necessary modifications may be applied. And finally the CLDATA is generated and can be used to generate machine control data or MCD which then be transferred to MCU (McMahon & Browne, 1998) (Smid, 2003).

2.7.4. Part programming exploiting 3D CAD models

The introduction of digital part and process planning in production was seen as a means to facilitate the realization of complicated geometries which usually result in complicated machining procedures. One inherent complexity in regard to in this approach is that to deal with multi-curved surfaces. Each digital application may offer a different strategy; however, it is important to define any set of machining operations such that independent tool paths do not impose on the previous or subsequent generation of an object feature.

Basically operators should be aware of procedures that may have been chosen automatically because in practice two or more of them can interfere with each other. Bulk removal of materials using CNC machines may create a rough surface where material has been removed to various depths. Due to the existing details of the 3D digital models production engineers possibly have to plan for more than one round of machining. Based on the required level of finish on the work pieces after bulk removal of materials, the piece may undergo similar but slightly different course of machining to provide the desired smooth surface using different thicknesses of tools existing in the tool magazines of CNC devices. The following machining activities can also be totally distinct from what has happened earlier in the production line. For example, we can have cutting and milling and then brushing on one work piece. The planner has to plan the process and the hierarchical flow of activities to reach the intended result of the design. It is fast and easy to use automated planning applications but sometimes the final product of these plans do not match the design criteria since the parameters which have been defined in some applications do not let them plan totally accurately. Based on this fact constant supervision and manual evaluation on the production line is still necessary in order to prevent unexpected errors in automated translation, providing the direct CAD CAM link (Smid, 2003).

2.7.5. Prototyping

In most models of design there are phases for testing and development. For instance in Pahl's model of design we can find the embodiment of the design activity in a process that comprises operations for detailing the concepts and design development by removing defects and deficiencies. In this stage it is vital to analyse the resultant design proposals and to refine them in order to fit the intention of the design. The realized interim models of design proposals which are used to improve the quality and/or function, stability, choice of materials, geometrical reasoning and production planning or even marketing of the end products are all part of the process of developing prototypes [Figure 2 .55]. Although the concept which has existed previously in regard to prototyping was mostly limited to physical models which represented geometrical and other physical features of objects; yet, nowadays thanks to highly improved and capable computer hardware and applications we can benefit from instantly produced physical prototypes [Rapid Prototyping] as well as digital prototypes which can accurately represent almost all of the features of the products without the need for making physical models or mock-ups for tests. Physical models or prototypes that used to be made of wax and clay formed by hand or using handmade casts during a slow and labour intensive process now can be made from a vast diversity of materials and methods including automated digital techniques.

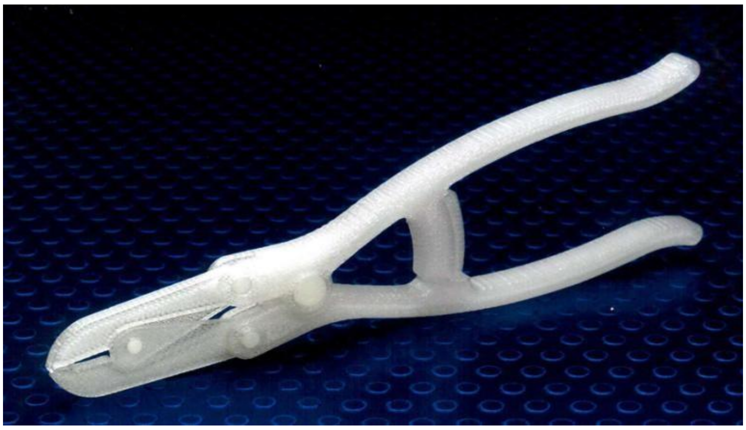


Figure 2 .55 Prototyping
Prototypes are models of products replicating one or more of the final products' features used for testing and sometimes marketing purposes. Picture (THOMASNET.COM).

Since time has become a decisive factor in the tight competition between companies, they all aim for a reduction in the amount of time that it takes from the inception of the design to the moment when users receive their products, a factor which is known as 'time to market'. As previously explored, a simultaneous process is a mode in which time saving is a principle of its feature. In such an approach prototyping techniques become critical.

One of the advantages of the direct link between CAD derived three dimensional models and CAM devices, is the ability to leverage the rapid prototyping technique.

Rapid prototyping, which is also known as tool-less manufacturing, desktop manufacturing and solid-object modelling is considered as being comparatively new. The first techniques demonstrating such a capability were created in the late 1980s. In fact, the intent of such methods is to create physical models of the design at a fast speed and totally performed by machines. By improvements of CAM devices, rapid prototyping sometimes has been used to manufacture very high quality objects in a limited numbers. There are many types of rapid prototyping techniques and strategies which can be applied dependant on the geometry of design or application for the resulting prototypes (Schodek & Bechthold, 2005).

2.7.6. Robotics

We know that NC machines can be programmed by commands which run motions that operate on the work piece. Robots can be categorized in the same family as numerically controlled machines but with a much broader range of applications (Figure 2 .56). Robots are programmable devices which can be used in many industries and carry out different jobs. In areas where there is a need for ultimate accuracy, which sometimes humans are not capable of, heavy jobs and faster and repetitive processes that may have negative physical and mental influences on human workers robots have been used instead (Owen, 1985).

Drastic improvements in mechanics, electronics and computing have evolved robots from just being mechanical tools only capable of following pre-programmed commands and performing a limited number of movements to the point where they can interact with the dynamic and natural environment and other man-made devices. They can collect information, process data and make appropriate decisions and perform the right action.

In the United States at the end of the first half of the 20th century the 'Argonne National Laboratory' developed the first robots that were used in atomic plants to perform tasks which could be dangerous for humans. They designed a system capable of copying the operators' movements where sensors were used to collect human movements and transmit the controlling signals to robots (McMahon &

Browne, 1998). During the next decade the potential of robotics grew and many control devices such as joysticks were introduced to the market. More than a decade after the birth of the first robots, 'Unimation Inc.' made significant advances and created automated robots, so that while older machines needed constant attention and could only copy the operator's moves, new ones didn't need to rely so heavily on their human operators (Waurzyniak, 2006). Throughout the next two decades [1960s and 1970s] the development of robotics became the interest of numerous scientific institutes and engineering companies which brought a number of new control and feedback systems into the field. But 1980s was the time for robotics to become widespread in miscellaneous industries. The growth was so fast that, for example, in a three-year period prior to 1987 the number of industrial robots in Japan and United States doubled. Up to until the end of the 20th century robots have been used for industrial and repetitive works such as assembly and painting, nowadays they have become more and more involved with softer materials due to their ability for increased control and delicate motions. Today it can be witnessed that many medical operations are being performed by robots as they can guarantee more accuracy than humans when for example performing surgical operations on the eye or brain (Malcolm, 1988) (McKernon, 1991).

Figure 2 .56 Robotics
KUKA robots in a car factory. Robots are widely used in production lines. Picture (Wikimedia-b, 2012).

2.7.7. Cellular fabrication

Traditionally what companies might expect from a production process was to collect all of the necessary fabrication machines under one roof and then start planning based on their capabilities and installed capabilities. For complicated products composed from several components which have to be made by different machines after being machined the parts needed to be transferred between machines. Such process was considerably slow and hard to plan and there had always been problems with the timing of manufacturing operations as different machines may work on different parts at different rates and to adjust them for new works would take some time; in addition we have to consider the technical issues with the machinery. The newer version of an organization has to specify the machining process and manufacturing devices which are needed in order to produce components. Based on this information companies group their machinery in ‘cells’ so parts can easily circulate amongst machines towards the end of the production process and the machines are located in the functionally appropriate cell. Thus time and energy consumption reduce and production planning and timing become much easier. In fact most of the technologies and methods which have been described in this chapter are necessary for cellular production. As it has been mentioned previously, regular changes in design demand flexible systems. In cellular production systems every cell has to be able to manufacture a large variety of a product family. In order to progress towards that point they need to gather the following technologies and methods in their system of work.

- **GT** to identify the part families.
- **CNC** to automate the processes and be programmable as a versatile tool.
- **Tool magazines** and controls so machines are capable of different actions.
- **Robots and automated** transfer of components to facilitate timing, assembly and delivery.
- **Controls and sensors** to analyse the process and products and send feedback to the system for further decision making and possible changes.

- **CAD CAM link** to have automated manufacturing procedures and zero defect products and production planning. It also provides a great connection between all project groups and better control on machining process (Syresh & Kay, 1998)(Black & Hunter, 2003).

2.8. Production processes, customers and suppliers

2.8.1. Introduction

The following chapter intends to introduce different aspects of manufacturing planning systems and offers a brief overview of related fabrication systems. Initially by defining the discrete fabrication of components and describing the contrast with the continuous production process, the intent is to show the characteristics of various production strategies being applied in this system. Through the next part of the thesis a brief presentation of the different production environments which can be organized based on a range of fabrication options is illustrated in order to discuss the character of each environment and point out the merits of each. Reviewing the historical timeline related to an industries' organizational changes we will see how customization and customer-driven production have become the mainstream of today's manufacturing systems. In the following sections the value of lean engineering is clarified as to its role in making customized production profitable. And finally the concept of 'business process reengineering' (also known as BPR) and its importance in modern companies is introduced.

Despite all the technological and organizational improvements production planning and evaluation of the processes are still a complicated task, although it is a definite fact that the degree of complexity of the job is dependent on the complexity level of a clients' demands. Designers must analyse customers' requirements and try to find an appropriate response to those needs by converting the data to objects, each comprised of different families of components. Manufacturing processes need to be organized and then individual parts are fabricated which is normally followed by subassemblies and assemblies and ultimately delivery to the customers. Factories may fabricate all of the required parts for their products or may also acquire some from other factories and suppliers. Throughout all of these activities, planning for details such as time, cost and availability of raw material or parts is also of a high level of importance.

2.8.2. Discrete component fabrication

There are many ways to categorize factories; one of which divides them based on the nature of their production process. In this classification there are two groups of factories which apply either discrete component fabrication or the consecutive system. The latter system runs a consistent fabrication process that may apply mechanical and electrical as well as chemical processing techniques from the beginning right through to the end, usually in a dedicated production line [for example the production of canned food products]. Going back to the first group which would be termed discrete fabrication, the process is designed for the fabrication of each component singularly. The discrete production process may apply in three distinct types of approach namely mass production, batch production and finally jobbing shop production. Although these three groups stem from the same origin amongst the fabrication categories in factories, nonetheless the results of their application are characteristically different [Figure 2 .57] (McMahon & Browne, 1998).

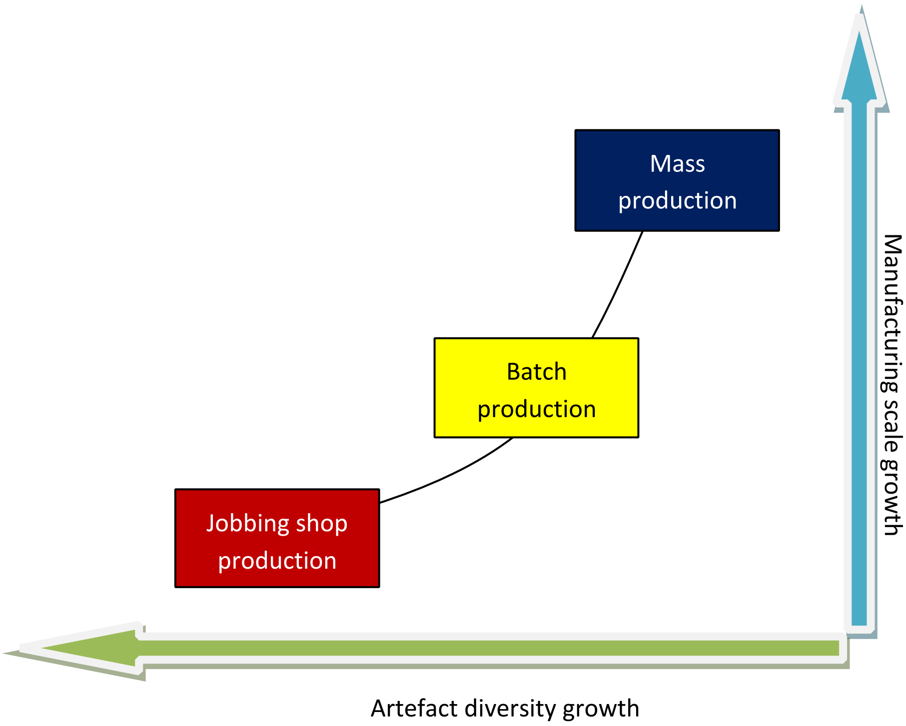


Figure 2 .57 Discrete fabrication

Types of the discrete fabrication approaches in an artefact diversity and manufacturing volume contrast diagram [drawn by the author based on (McMahon & Browne, 1998)].

The main feature of the mass production approach is to manufacture a limited variety of products but in a considerably large number. In such systems every aspect of product and procedure are as standardized as possible; in fact there is almost no space for customization. Compared to other two systems, mass production manufacturers are the least flexible and considerations for changes in short and medium terms are mostly applied as minimal alternations. Mass production systems in factories are sometimes named as 'Detroit Style Automation' and 'Hard Automation'. Mass production machineries are usually designed for the production of a very limited variety of products which certainly have a stable market and therefore sales volume is guaranteed and the prospect for changes in the close future is near to zero.

In contrast to mass production, batch production is a system based on conformity of processes and/ or features of artefacts in relation to the variety of products and quantities of the intended manufactured products. The naming convention given to this method is due to dividing products in relatively small batches based on their similarities and performing manufacturing operations on each batch separately and when the operations are finished on all objects in one batch then they all move through to the next round of operations together or, depending on the production line, in smaller or larger numbers. The machinery should be more flexible compared to mass production devices. Machines need to be responsive to short term changes based on clients' demands or the market's fluctuations. Since moderation runs through all aspects of this approach, it can be placed between the two extreme approaches of total mass production with almost no elasticity in response to sudden changes or customization and the concept of jobbing shop production; when the number of required products is going to be low then it is more economical to custom manufacture them but when demand is higher it might make more sense to go for mass production.

The major characteristic of the last production method which is jobbing shop production is the high level of customization. Due to the fact that most of the time the results of such production methods are going to be absolutely unique, as standardization has been reduced to almost zero and production would commence based on customized features, consequently each product passes through unique fabrication procedures; if not all, at least most of the components are going to be slightly different from one product to another. As a result the production time will grow dramatically and the number of finished products falls. Competition here is to stretch as much as possible to integrate with every single expectation of customers. As a result the fabrication line and machinery should be extremely supple and capable of performing a large variety of fabrication operations. Working with such systems requires an exceptionally experienced operator, usually experts in a variety of fields. Concepts of 'make to order' or 'engineer to order' are basically related to jobbing shop production (Jagdev, et al., 2004).

2.8.3. Classification of fabrication approaches

Mass production techniques are still popular all around the world and in various industries; but, growing demands and unstable market forces push mass producers toward batch production integrated organizations. Users increasingly expect companies to produce products with different designs. In fact customers put their faith in factories which provide customized goods. In contrast to the higher quantity of products which was demanded after the Second World War, nowadays the quantitative shortage of products is not an issue, thus companies try to attract users to their products by producing personalized items that can answer to the needs of individuals. A few even go a step further and make claims about a rapid move to 'one of a kind' production (Higgins, 1991) (Wortmann, 1992).

High standardization of components has lead customers to choose certain type of products which are available on the market and are intended to be used by a large group of users, even though their experience may not always be satisfactory regarding the fulfilment of all of their needs. Factories used to mass produce artefacts and then delivered them to places where they were stored. Users then had to acquire goods from those stores so basically they had no direct connection with manufacturers.

It was only in the late 20th century that companies found that competition with other companies became tighter and so tried to run a feedback system to contact users and develop their products actually based on studying the users' needs in greater depth. Now companies and users have different means of communication. These connections do not follow the conventional recourse of the users to lists of products to choose what fits their needs the most. Some factories now provide facilities that let their customers contact them and interactively order a fully customized product (Browne, et al., 1995).

Due to the level of connection between users and factories, the production settings can be grouped into four conventional categories. When factories produce their products based on a very well defined anticipation of the pattern of market expectations, they usually have minimum direct contact with their clients, the product variation range is limited and the number of products is relatively high. Those factories have adopted a 'MTS' or 'Manufacturing to Stock' environment. Due to all of these characteristics the delivery time is distinctively short but it is not a surprise that users are not capable of modifying the products based on their personal requirements. As an example of products from such environment we can nominate IKEA's cheese grater [Figure 2 .58]. The business planners in IKEA have anticipated the market and they know it will be bought and it is something that users usually don't see the necessity to change the standard design so as to modify it based on their own preferences.

Figure 2 .58 Manufacturing to stock

IKEA’s cheese grater. Picture (IKEA-a).

In the second group of production environments, factories have only medium connection with their customers at the sales stage. They provide a variety of products based on the core assembly of their products. The diversity is caused by multiple subassembly details which are determined by users’ preferences, yet interchangeable options remain limited. The Company performs the final assembly operation only after receiving the customers’ order which is called ‘Assemble to Order’ or ‘ATO’. Factories that adopt this environment try to keep the delivery time medium to short by over production of subassembly components nonetheless the delivery time still remains dependent to availability of optional components. Again we can nominate an IKEA’s product as an example; fabric sofas which can be ordered by specifying a preference between different styles of covers [Figure 2 .59].

Figure 2 .59 Assemble to order
IKEA's sofas with variety of covers. Picture (IKEA-b).

Some companies go a step further and not only offer optional subassemblies but also produce artefacts with different core systems. 'Make to order' or 'MTO' integrates broadly with users in sales and sometimes at the engineering level where production starts only after receiving the order. Two final products of such an environment may not only carry diverse visual characteristics but offer largely differing physical and performance features. Today we can find many car plants that set their work system as a MTO environment where they may produce sport, family, hatchback and SUV automobiles. Each model may offer many variations of engines or gearboxes and bodies may come in different colours or with various interior and exterior trim options. Car production companies may also have some subsidiary companies offering additional choices of body kit or engine tuning options in addition to the standard products [Figure 2 .60].

Figure 2.60 Manufacture to order

Mercedes Benz E-class Cabriolet. Two cars of the same model but with different details.
Right, standard model. Picture (Mercedes-Benz, 2013).
Left, after the Fab-Design's amendments on the standard model. Picture (Fab Design, 2013).

The last group of fabrication environments which is known as 'Engineering to Order' or 'ETO' can be regarded as an advanced version of the make to order system. The difference is in the superior influence of customers on the engineering process of production. The design of such engineered products is based on users' demands. Features of such a fabrication environment can be witnessed in architectural projects where architects design and construct buildings based on their clients who will be the future users of the building.

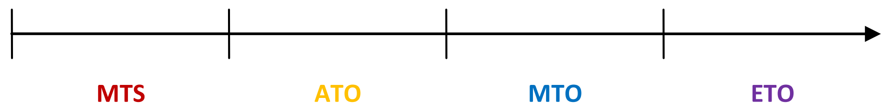


Figure 2 .61 Fabrication evolution

Top: Direction of fabrication evolution. Based on (Scallan, 2003).
Bottom: Characteristics of different fabrication approaches showing their differences. Extracted from (Wemmerlov, 1984)

Aspect	MTS	ATO	MTO
Factory/Customer Link	weak	At sales and limited	Design, engineering and sales
Delivery Period	Low	Mid	High
Production volume of each sales unit	High	Mid	Low
Variety of products	Low	Mid	High
Main Production and planning factor	Prediction	Prediction and Backlog	Backlog
Basis of Order Capacity	At hand Product inventory	At hand Part inventory	Capacity of customized production
Dealing with Market demands	Safety stocks of sales units	Over planning of components and subassemblies	Limited uncertainty
Time planning bottleneck	Sales	Main Components and subassemblies	Finished products Finished parts and assembly
Finishing assembly timeline	Close correspondence to the master schedule	Dependent to orders	Includes most of the assembly operations
Quantity bills	A Standard BOM per each sales	Planning BOMs required	Unique BOMs are produced for each customer

Up to this stage the intent has been to differentiate companies based on their systems of production and customer interface but it is essential to know that most of companies do not choose a single approach in their fabrication systems. Those companies are termed hybrid. For instance, factories may produce their most popular artefact in a large number as a standard product but also offer a number of variations of the standard product [e.g. variety of colour, memory space in electronic devices, finished surface material]. Accordingly we can summarize that companies working as a hybrid of the MTS and ATO approaches mostly deliver more satisfaction among a larger number of customers, therefore generating larger benefits for the company. As illustrated in the Figure 2 .61, over the passage of time and especially during the last thirty years, there has been a higher tendency toward Engineer to Order which shows the trend toward catering to a specific customers' need. However, this paradigm shift was not possible without the revolutionary innovation of computer databases, digital modelling and computer-integrated design support applications and devices as well as CIM (Computer-Integrated Manufacturing) machinery (Scallan, 2003) (Jagdev, et al., 2004) (Rolstadas, 1991).

2.8.4. Linking factories to users and providers

The previous section of this chapter defined different fabrication environments and explored the paradigm shift from the 'manufacture to stock' approach towards the 'engineering to order' trend which speeds up as time passes. This tendency towards the order-oriented fashion demands a high level of customer interaction. Customerbased production requires sufficient communication between producers and customers to manage their needs and provide feedback and to do so, companies have to be capable of making quick changes in design and fabrication directions. Despite all the benefits of the customer-manufacturer link, it cannot guarantee the full satisfaction of the users by its own. Manufacturers know that the speed of their response to the customers' demands is highly related to the delivery of raw material, parts or services through outside providers.

These understandings accompanied by modern computing and communication technology have brought about the generation of the 'extended enterprise'. This term is used for a group of self-organized companies which are working individually but towards shared interests in completion of certain strategies, gathering their resources in order to provide products or services for their users. This link is defined due to the relation of their work together and is not based on organizational mergers and can be regulated by contracts. The benefit is a competitive advantage due to the linkage, for example, between manufacturers, suppliers and distributors. Previously industries have only been focused on productivity improvement and optimization in the immediate area of operations of their companies whereas now they have to involve several other factors in process planning, consideration and calculations (Browne, 1995) (Warnecke, 1993). In Figure 2 .62 there is a basic demonstration of the link between manufacturers, suppliers, distributors and customers.

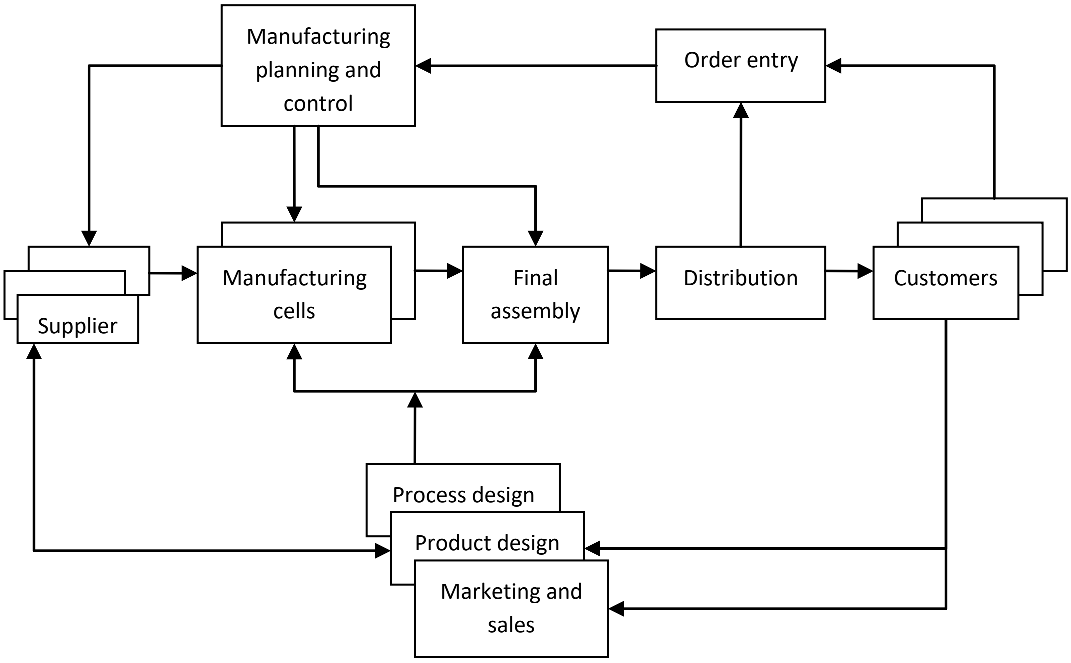


Figure 2 .62 Production links
Links between various parties. Diagram based on (Arlbjorn & Haas, 2010).

2.8.5. Lean production processes

By looking at the history of industrial production it can be witnessed that after the age of craft production which was followed by mass production, as a result of the work of the international motor vehicle programme research team, lean production has been introduced as the newer generation of production mode. It was in the absence of NC and mechanical fabrication devices that highly expert craftsmen used relatively uncomplicated yet mainly adjustable tools to create unique objects with almost exact relevance to users' needs; thus there is no doubt about the process being time, labour and consequently cost intensive. As quantitative product demand increased and technological developments paved the way for mass production, skilled technicians designed products in response to the market requirements and also planned fabrication procedures which could end up producing artefacts using costly and highly dedicated machinery but with cheap, unskilled workers.

Mass production stood as the leading trend in manufacturing environment until the mid 20th century when Toyota realized the need for having a deeper regard toward users' needs. At that time endeavours were focused on the formation of a system carrying the positive features of both craft and mass production yet avoiding the extreme standardization of mass production as well as cost and labour intensiveness of craft production (Womack, et al., 1990). The car company planned to produce larger variation of car types to meet market demands, in contrast with western companies such as Ford that were focused on an highly standardized process to gain better productivity. In order to keep production profitable in this new system, engineers tried to reduce machinery installation and setup time. Instead of concentrating on the optimization of the fabrication process itself, many efforts have been directed toward the generation of new design, manufacturing and quality control ideas and the formation of allocated providers empowering the supply chain links with providers and distributors. As a result of strong distribution planning dealers became an inseparable part of Toyota's car production system and a dealership network grew which led to the company's gradual diversion from mass production to an MTO environment. This systematic shift in Toyota's business model has led to the realization of user-oriented production which did not exist before that time and known as Lean manufacturing (Black & Hunter, 2003). From the mid 20th century on, many studies have been run to identify the effectiveness of lean production in various industries, among them the international aerospace program, to survey the lean production process in the British aerospace industry in early 90s. From the productivity and optimization point of view, results demonstrate large similarities to what has happened in the area of car production. The essential point here is that there is no limit to what can be involved in the optimization process. Any possible factor should be considered and if its value was proven then it has to be planned and integrated with all other elements of optimization. In addition, companies have to embrace any radical changes that can develop the links between all parties of an enterprise and increase productivity (Black & Hunter, 2003) (Black, 2008).

By all means, lean production intends to minimize any sort of waste during the production of any kind of artefacts. In a lean system, causes of waste are not only a consequence of time or material consumption; some other organisational defects like overburden also can cause waste. In essence the goal of lean production is to reduce waste and non-value- adding activities to increase productivity (Womack, et al., 1990)(Holweg, 2007). After the reduction of waste, in the second wave of lean concept development, the prime consideration is to level different sequences of work and resources to achieve process smoothing; thus trying to eliminate waste and increase productivity in a systematic manner (Liker & Houses, 2008).

In the lean concept there are seven main sources of waste:

- To move material or products. This activity does not add value to the final product and considered as waste.
- To move workforce and equipments.
- Buffering or storing material or products.
- Set up time in one part which can cause the production line to stall in other parts.
- Manufacturing products over or below the market demand
- Over processing
- Lack of quality in final products or not matching the market demands (Womack & Jones, 2003).

Similarly in construction, the lean concept has been utilised to improve the design and construction of buildings. Such a concept in the construction industry considers design, building, and environment. The desirable result is to make buildings with as little as possible costs [financially and environmentally] and as much as possible in terms of added values [to the built environment while considering client demands] (Koskela, et al., 2002).

Lean construction has a holistic view towards the industry; therefore it considers market, clients, designers, local authorities, suppliers, builders, etc. In fact the Intent Has had been to initiate a “way to design production systems to minimize waste of materials, time, and effort in order to generate the maximum possible amount of value” (Koskela, et al., 2002). Such a goal is only achievable through the cooperation of all construction project stakeholders from the conception all the way through completion and lifecycle of the building products (Abdelhamid, et al., 2008).

Later in chapter 3 some examples of lean construction in practice have been demonstrated [Especially in the work of Facit homes which is briefly shown in chapter 3.6].

2.8.6. Restructuring the workflow

New computer-aided technologies have changed the business structure of modern companies. The emergence of CAD, CAM and CAPM (computer-aided production management) linked together by strong electronic data interchange systems have begun to facilitate the user-manufacturer connection and brought bout an exponential growth in productivity. Meanwhile, applying these innovative techniques in some cases did not always lead to the level of success which has been expected. Some experts claim that developments have not been harmonised in all respects especially in relation to IT aspects. In most cases companies who are intent on using modern technology to just rectify problems resulting from conventional methods and are not realising the benefits of fully adopting modern systems by doing an organizational change since you "*do not fix what isn't broken*" (Lyons, 1995). Following the theory of "*if it isn't broke, don't fix it*" made business owners only see the apparent benefit and miss the long term success. Tackling this concept, Hammer asserted in his article advising companies to 'don't automate, obliterate' and proposed the reengineering of the entire business process for factories (Hammer, 1990).

Reviewing different approaches to organizational change, it can be witnessed that many of these, such as 'just in time', 'total quality management' or even 'world class manufacturing' support the gradual and constant system development whereas business process reengineering suggests radical and fundamental conversions (McSwiney, 1995). The former group of systematic changes only propose changes in fabrication workplace while the latter considers all parties in a large group and applies systematic changes all over the organization.

In chapter 2.8 different types of manufacturing strategies and consequently those factories which are shaped by them have been demonstrated. It can be seen that traditionally there are several different approaches towards production and based on each traditional approach used by factories their products and services are shaped and characterised. It is also mentioned that computers are changing this traditional categorisation and move the production in different industries into a new era where definition of production strategies, features of the end products, clients-producers links, productivity and efficiency are redefined. In fact computers have helped some manufacturing philosophies such as lean production and lean construction to come out of the traditional mould and be able to become closer to reaching their ultimate goals [waste elimination, matching market demands, using the economy of mass production but matching the each client’s exact expectations, Etc.] through the revolutionary organisational changes suggested by new potentials and made possible by new flexible tools.

2.9. Ultimate optimization and idealism

2.9.1. Introduction

This chapter aims to define the 'Just in Time' concept also known as the 'JIT', focusing on its influences in design and the manufacturing industries. Following the discussions from previous chapters, we will have another look at product families and flow-integrated fabrication and their application in the 'JIT' approach. In order to have a comprehensive review on all aspects of the JIT, one part of this chapter is dedicated to demonstrate the quality of manufacturer and supplier relationship as well as defining design strategies which are useful or even sometimes play an essential role in the route towards gaining the best results from this system. Similar to any other production strategy there are also fabrication planning and time management methods.

The term 'Just in Time' or 'JIT' is used to name the concept of ultimate optimization in production. Although integrating with this concept may be regarded by the Western business owners as the only solution for them to conquer their Japanese and Chinese rivals, who established the JIT concepts, in the international market; but considering the limited energy and material resources and growing demand for products it may be the inevitable future of industries all around the world whether for the purpose of competing with other companies or surviving through the new market demands, supply capacity and environmental rules (Imai, 1986).

2.9.2. The 'Just In Time' approach

Ultimate optimization, hundred percent efficiency or perfectionism in production are all attributed to the just in time approach and serve to theoretically define its goals. In practice, JIT seeks to push all the limits to attain the best possible distinction in every single part of the production process to produce perfect products causing the least waste. In fact, JIT demands only the amount of perfection that is requested and any excessive quality over that needed and planned for is also regarded as imperfection. Based on the just in time philosophy, the intended productivity, efficiency and quality is the result of the synchronization of actions in order to provide the correct items of the right quantity and quality in right time and right place (Cheng & Podolsky, 1996).

In the JIT system of production there are important points that needed to be addressed. Almost all of the production specialists are aware that currently the theoretical goals of the JIT concept appear to be rather undeliverable not to say unrealistic. The unattainable qualities are clearer when we try to turn defects, setup time, inventories, handling, breakdown, lead time all to zero in the imperfect world of manufacturing. JIT concepts are basically unsustainable in traditional fabrication environments where all the efforts toward the Just in Time goals frustrate (Schneidermann, 1986).

It can be said that the success level of JIT is highly related to the cultural characteristics of the place where the production is happening. The work environment in eastern Asian countries is more groups oriented which is quite different from what exists in western countries where individualism is more dominant.

The conventional problem solving approach in production is to break down complex sets of problems, geometries and structures by another simpler set and then solve the smaller and simpler problems or plan for each shrunken down element's fabrication. This caused the generation of specialists, each expert in a limited aspect of production function while there was a limited window towards the comprehensive overview across the process. Just in time on the other hand considers the totality of projects in order to achieve to its objectives.

Managers of factories conventionally consider manufacturing defects as an unavoidable result of the production process and the focus is to keep the amount of defects in a so called 'tolerable' zone. Thus the intention of producers would be to provide maximum satisfaction, as far as possible, for users. This trend does not conform to what just in time intends to achieve. The JIT tries to investigate the systematic shortages that cause defects and fix them appropriate to the zero defect concept.

The JIT assertively claims that inventory is a product of mismanagement in planning, design, teamwork, communication and shop floor performance thus the progress should be directed toward the elimination of inventories which play the role of shock absorber. This function was necessary in traditional systems where suppliers were unreliable in regard to providing raw material, subassemblies or services as they are needed and on time. Traditional companies consider inventories as they can be regarded as the 'work in progress' and the stored manufactured products with their added value as their 'financial potentials'. Inventories also appear as a guarantee to the company's survival in the event of management problems in supply or unavoidable misconception of market fluctuations.

Another goal of the JIT approach is the zero installation and adjustment time for machinery. When we think about zero machinery adjustment time in our work we also have to bear in mind that in such concepts, and referring to batch production characteristics, there is no benefit in grouping parts in batches. In order to reduce the inventory costs in factories they try to create a balance between transportation costs of batches and installation and adjustments costs. Basically large groups of parts or batches impose higher inventory costs and smaller groups might cost more due to the need for more adjustments and setup time. In a system where adjustment time and costs and inventory costs and space are pushed to zero, then a batch of individual part is the most efficient.

When designing a production process, framing it within a long period of fabrication requires the process strategies to rely on forecasts. Companies need to allocate more time for processes to cover the unpredicted problems which are harder to anticipate over a longer period of time. It also means that the production lines have to be devoted to the production of one object for a long time. Just in time suggests zero lead time as one of its goals. It means that planning gets much easier as it is shorter than before causing less unpredicted problems that may endanger the project. In parallel the system is going to be involved in one project for a shorter period therefore it is more flexible and responsive to unforeseen obstacles and changes. Mentioned before, conventional methods regard design and manufacturing as discrete activities whereas just in time's thorough view identifies the affiliation of them. The value of this concept is undeniable in regard to reviewing the growing market and demands for more customized goods in shorter time spans. Although the actual zero lead time is unattainable never the less the valuable efforts of companies to reduce lead time have been certainly financially beneficial and their production environment is more responsive to changes. These factors can make companies appear as being superior compared to their rivals.

In every production project there are numerous activities needing to be performed to fabricate objects which do not necessarily add any value to the product. Thus it is beneficial to consider reducing them to the minimum possible. As an example we can take a look at assembly process in factories. Assembly operations generally consist of part feeding, handling, mating, testing and quality control and other possible special activities. For instance the part feeding stage does not add to the value of the final product hence if we plan to reduce the feeding process to the minimum we will have a more efficient process (Cheng & Podolsky, 1996).

2.9.3. Ruling factors in JIT based systems

According to the goals of a just in time based system which have been mentioned in the previous section, we can now point out some ruling factors of such systems. To begin with is the need for direct communication with users since the designs should match the market demand as much as possible; secondly the use of group technology and any other methods to facilitate the flow-based manufacturing environment; and last but not least is the highly prioritized well established connection with supply chain to guarantee constant feed into the system.

These factors rule a production method in factories with two ends; the front end links the factories to the users and the back end connects them with providers and suppliers. As it has been said before, JIT has a holistic view to the production environment and seeks to improve the organizational efficiency through developing each part of the system in relation to all the others. Consequently a JIT approach is not limited only to manufacturing and involves other activities such as marketing (Hernandez, 1989).

The importance of conversion in direction of manufacturing strategies according to the growing expectations of the market has been discussed previously. It has been established that although all aspects of the production industry has been developed dramatically specially during the recent decades, therefore fabrication of highly customized artefacts is still enforcing higher costs on factories compared to what mass produced standardized products do. Therefore factories chose a strategy in which they analysed the market needs and behaviour and based on these data they grouped their customers due to the similarity of their interests and designed and manufactured a range of products such that each class of products responds directly to the needs of at least one group. In order to pre-empt the market and surpass other opponent companies in the same industry the diversity of produced goods should be large enough to satisfy almost all customers' tastes and products also should be offered at a reasonable price to be affordable for the targeted market (Knight, 1974).

One of the ways to gain efficiency and productivity in addition to customization is the 'modular approach'. As has been mentioned before, the more the variety of products, the more manufacturing, set up and assembly costs they cause. Factories also need a system capable of being responsive to frequent changes. Basically as managers increase the flexibility of their systems at the same time they put a heavier financial burden on the company and consequently their products are going to be more expensive. In a modular fashion engineers try to inspect various groups of products so as to spot similarities between different groups, in fact there is much effort focused on increasing these correspondences. Such methods cause considerable reductions in production time, machinery set up time, assembly costs, less part design and drawing etc. (Yoshimi, 2008).

In JIT the strategy is to form a firm and sustainable link to certain providers. Instead of circulating between different suppliers, factories must find a reliable provider which can meet the factories' timelines and standards. They can share comprehensive and detailed process data of their works; thus the manufacturer and supplier can help each other in overcoming problems and with a good understanding of how the manufacturer and supplier work together it is more likely that they can establish a more efficient environment. A sustainable manufacturer provider link needs a long term plan so that each part can realize the goals on which the connection is based and help one another to develop their capabilities. A more synchronized relationship between them two means the greater flexibility of the production volume and character (Lubben, 1988).

2.9.4. Design considerations for fabrication and finishing

It has been said that designing through recognition of an exact set of market expectations is one of the ruling factors of the just in time approach. One of the necessities for a design team is to adopt a user's needs in their design proposals and/or even manage the users' choices by diversity of their products which are responsive to the market if it is possible. It has also been mentioned that in order to make the activities of a production companies' successful, it is essential to produce artefacts to satisfy a wide range of customers as well as products being offered at a reasonable price so as to be affordable for the targeted users. These goals are achievable in a number of ways. For instance factories may choose strategies to grow the number of their product groups by keeping the processing operations low at the same time (Kusiak & Chow, 1987) (Lewis, 1986).

The relationship between the diversity of products and the process variety has been demonstrated in the Figure 2 .63. The Figure 2 .64 shows how the process and product variety relation is defined by the two technological and financial constraints. The manoeuvrability of designers and manufacturing planners is within the diagonal strip which is limited by economic and technological limits. In order to illuminate the Figure 2 .64 clearer, we can attribute the bottom right corner of the figure to the mass production system since it resembles the features of that production strategy; and the top left corner has the jobbing shop manufacturing characteristics. Considering the current theme in production developments we can assume that the focus is in moving the process toward less process and more product variety which is located in the bottom left corner of the figure. Although the progress in this path is limited by the lack of technology, but the day by day technological developments especially in computer driven devices and generation of flexible manufacturing systems facilitates progress in this direction.

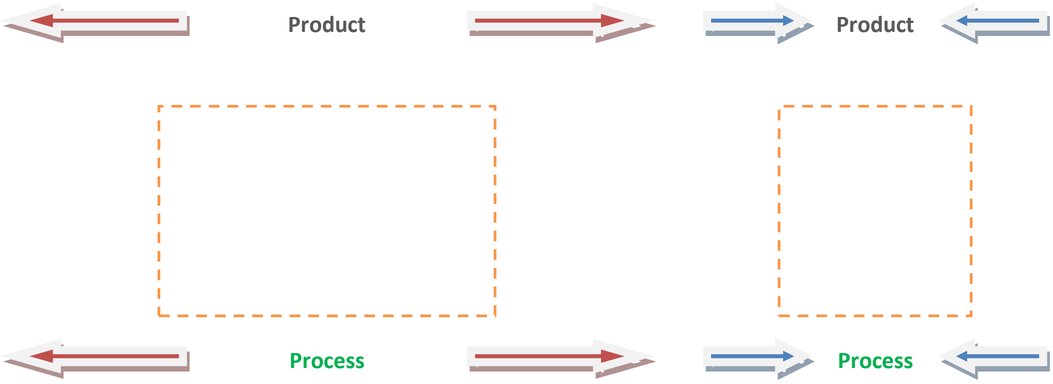


Figure 2 .63 Product variety
Growth and reduction in the product variety has direct impact on the variety of the production process.

Systematically speaking, the just in time trend offers a more thorough view toward this goal for the sake of more variety of products and less process. Technology progression is not the only area which draws the attention of JIT users. They also pay great attention to techniques such as fabrication and assembly oriented design, applying machinery and staff that have the fastest response to change, reducing the installation and adjustment time and cost, etc.

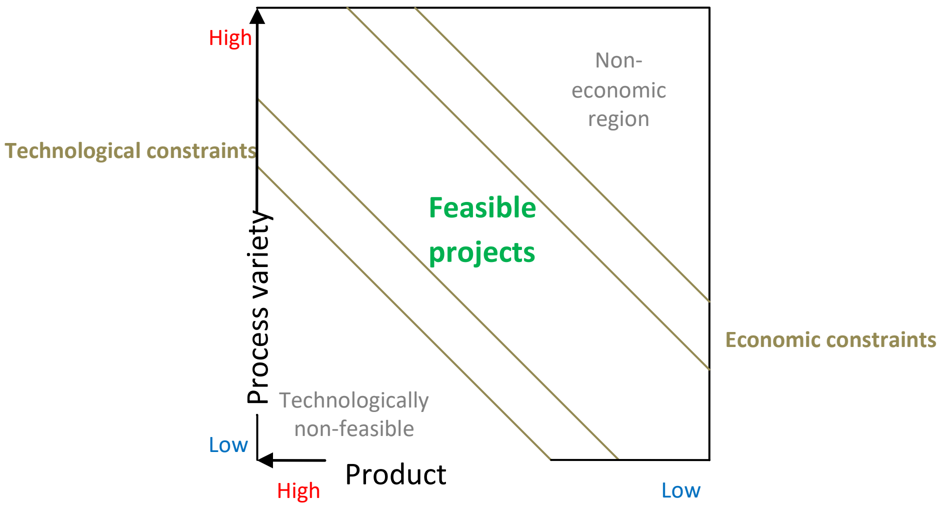


Figure 2 .64 Production limits Variety of artefacts and processes are limited by the economic and technological constraints.

A fabrication device which does a machining job on two different types of artefacts in a JIT system is desirable when it ideally requires zero or realistically negligible adjustment time after machining the first part in order to be prepared for the second product's machining. Such an accomplishment is only possible through the collaborative work of the design team, planners and production engineers (Cheng & Podolsky, 1996).

A desirable design proposal should decrease the number of necessary components for the intended artefacts' production; therefore the production time and cost drop dramatically. By other means a good design may consider modular components which use a repetitive assembly operation to form the final product in a variety of product families. Figure 2 .65 demonstrates a primary model of the modular design fashion where A is the common component in the three different product types 1, 2 and 3. The intention in this model is to raise the application of the A element. Accordingly fewer types of products are needed to be produced and production time and cost drop as well as the inventory costs and volume. This fashion is also influential on the bill of materials by trying to keep the differences between products as high as possible in the product structure and thus minimize the consequences of variability for manufacturing (Yoshimi, 2008).

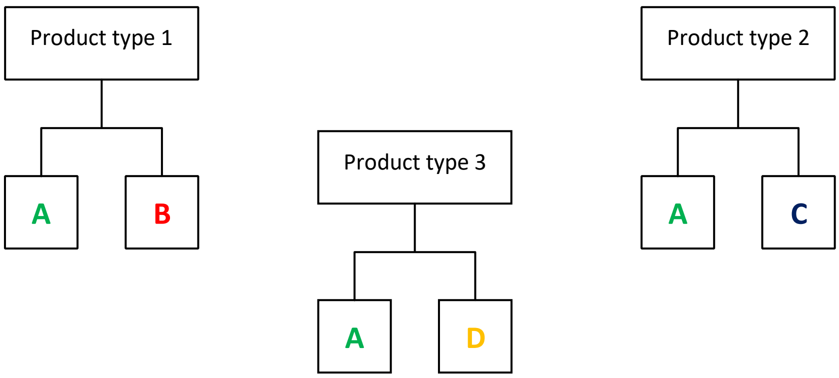


Figure 2 .65 Modular design
Modular design across bills of material. Based on (Yoshimi, 2008).

Nowadays designers mostly aim for the development of design proposals that facilitate the fabrication and assembly process. Modern product planning and design essentially needs to consider using off the shelf items as much as possible, standardized components or at least parts with the least possible experimental machining. Characteristics such as load bearing, finishing and so on need to be designed in regard to the important fact that unneeded fabrication operations force more financial burden on the company. Working with this view makes numerous positive changes towards simplification of design and subsequently simplicity of production.

Design for ease of automation's focus is on the common approaches and design concepts that will, for instance in the case of part assembly, supports the simplification of automatic components feeding, orienting and assembling procedures. As an example from the assembly operation, it is mostly essential to design parts to be physically assembled from the top down since in a production line it is the best strategy comparing to assembly from the sides or from the bottom of products in an automated assembly line. A desired assembly line configuration chooses operations with less complexity and tries to avoid any extra work.

Undoubtedly it is due to the application of robots and automated assembly process that the value of design for manufacturing and assembly is more apparent. Because of the limited capabilities of robots, for many years after they first had been used, their application in industries has been restricted only to basic jobs such as painting, welding or loading and unloading and they perform negligible roles in assembly. It has only been during the last two decades that robots also have largely been involved in assembly procedures.

Figure 2 .66 Da Vinci the robot

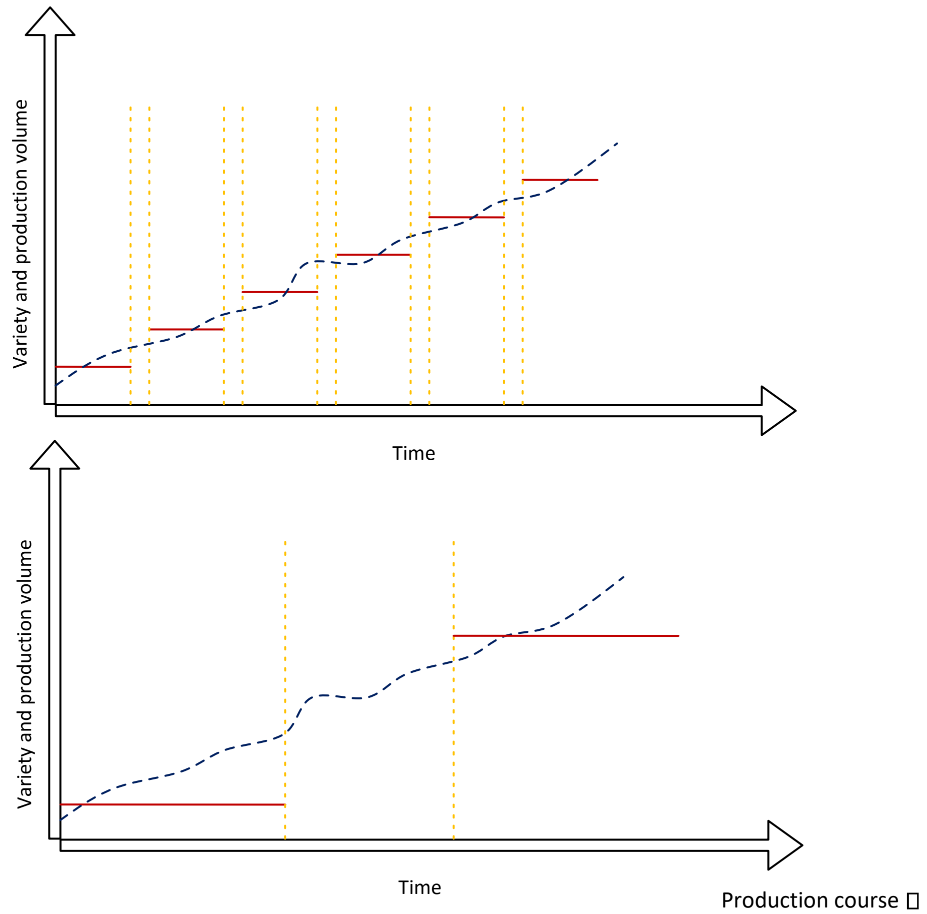
Recently, sophisticated robots which can perform activities with a high level of accuracy have been produced. The 'Da Vinci' surgical robot is capable of peeling a small grape without damaging its flesh. Picture (Southside OBGYN).

In order to make the best of robotics technologies, industries ran numerous studies in two major fields; on one hand engineers designed and made highly sophisticated automated machines to be used on assembly lines and on the other hand designers changed their design organization in a fashion that could facilitate the use of robots and automated assembly processes. The former includes the design of multifunctional clamps which can move in different directions and dimensions as well as modernization of control and feedback system which result in the generation of ultimately accurate and fast robots which can be programmed relatively easily. In fact it tends to replicate or even in some cases advance the motions and precision of human hands. Nonetheless it is the latter approach which appears to become more useful in production. A product designed in this manner reduces assembly to a series of pick-and-place operations, thereby requiring a less sophisticated robot. This results in manufacturing cost saving and increases the likelihood of financially justifying 'robotic assembly' (Billingsley, 1985) (Boboulos, 2010).

2.9.5. JIT and the fabrication process

Clearly one of the outstanding objectives of the just in time trend is to drop production costs as well as to increase the productivity of production lines. Factories may achieve financial efficiency through many ways; yet, one of the popular approaches is to minimize wastes in all kind particularly preventable inventories. For instance when distributing products for sale, the most beneficial system is to provide premium products in required numbers and appropriate price in the exact time when they are needed thus storage costs reduce to minimum. To match the true requirements of customers factory needs flexible tools and staff. Applying 'production smoothing' [Figure 2 .67] techniques, each production line is capable of manufacturing a variety of artefacts on a daily basis. Reduction of the process lead time is the most influential element in fabrication smoothing. Such a strategy may be applied in factories in two main steps. Through the first stage, reviewing and making changes based on users' demands on the basis of monthly intervals over a business year is applied and the second stage discovers the required changes on a daily basis throughout a month. To calculate all the required changes analysts may study changes in several consecutive years to predict the possible alternations to avoid seasonal variations and resulting business crisis.

Calculation and anticipation of the market demands over shorter periods of times helps the production line to be updated faster. Planning based on shorter periods also means that there are going to be much less changes in the production line and the design of the product to match the market compared to longer periods which may cause significant organizational changes that may damage the system. In order to make minor changes in the short-term, flexible machines are needed to allow margins for changes without a lot of time and cost consumption (Monden, 2011).



□ Market demands
□ Set up period

Figure 2 .67 production smoothing

Top: production smoothing has made regular changes in production lines and products. It keeps the set up time negligible and the products updated based on the market demands.

Bottom: In traditional methods of production, manufacturing reviews happens in considerably long periods of time. It makes the changes in every period significant and the set up time is also extensive. The production line is not flexible enough to absorb the market changes and keep the products updated.

2.9.6. Tactics for ease of fabrication and lead time reduction

Conventionally, in a traditional fabrication environment it is expected for the whole machining time [with the additional installation and adjustment time] to consist only 5% of the throughput of lead time. It is interesting to know that less than a third of that 5% is allocated to activities which actually add value to the product. The production lead time is often divided between four key phases. The machining time, the installation and adjustment time, the redeploy time and queuing time. A representation of throughput time breakdown is demonstrated in the Figure 2 .68. As it can be witnessed, in a production process the queuing time occupies largest part in the production lead time in some cases even up to 80% of total.

Adjustment time	Machining time	Transportation time	Queuing time

Figure 2 .68 Production time A schematic presentation of the throughput time dedication

Shockingly, most of the production lead time is dedicated to queuing and the movement of components between various operations stations. Therefore just in time suggest that in order to decrease the process lead time, factories need to reduce the queuing time which would have the greatest influence. In companies, product-based families decrease lead time by encouraging simplified flow of batches between activities and machining stations. In production lines however JIT suggests the application of the U-shaped layouts [Figure 2 .69]

The key intentions of layout planning for manufacturing in factories are firstly to support the flexibility of the workforce to adapt with process changes; secondly, to recruit skilled staff who can be operational in various work scenarios; thirdly, to upgrade their systems from being a single purpose production line which needs part transportation between machining stations; and at last but not least, to review and rearrange the traditional production operations considering radical technological and engineering developments.

Moving towards these objectives a u-shaped product based layout has been promoted [Figure 2 .69]. Such a workplace composition due to the close distance between machines enables multi-skilled Staff to be capable of working concurrently with more than one machine. It also helps to remove production buffers in factories. The success of this method shows the importance of the production line arrangement in productivity and efficiency (Monden, 2011).

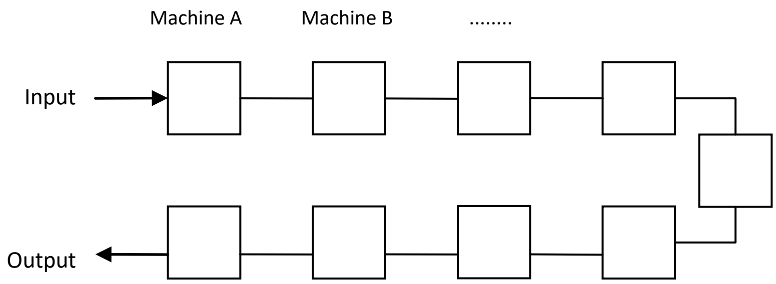


Figure 2 .69 Work cell U-shaped work cell. Extracted from (Monden, 1983).

Based on what is said before, reducing the queuing time can play a key role in the productivity growth mostly because it is not considered as a value adding activity and also because it occupies most of the lead time. The Figure 2 .70 demonstrates some influential methods that are involved in U-shaped production cells to decrease the queuing time.

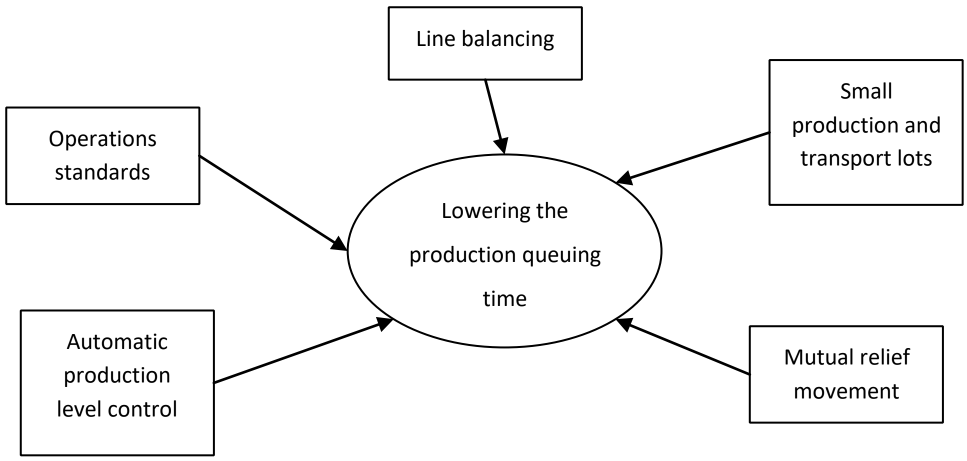


Figure 2 .70 Queuing optimization
Influential factors in queuing time optimization. Based on (Monden, 2011).

For example when in a production line one unit process a number of pieces in a certain period of time but in the next unit which has to process those pieces processing time is longer, it means that there has to be a buffer between those two units that holds the pieces that are processed in the first unit but waiting to be processed in the second one. Line balancing means that the processing activities are balanced between different units of a factory. Therefore there is no need to form queues between processing units.

In a JIT fabrication line there is continuity in the sequential work cycle. In such a system, by performing one fabrication work cycle, one unit of products is produced. By finishing each step of the manufacturing procedures the work concurrently starts on the unit in the next stage. This approach is already operational in mass production factories' assembly lines. Nevertheless mass production is based on lot manufacturing concept in contrast with the JIT that tends to develop the idea of unit manufacturing and redeploys systems also in fabrication activities and not just in the assembly line. Thus it is expected that similar to assembly lines, in production lines the machining ends in the former stage and start in the latter stage concurrently. This accurate harmony in sequences of operations is named as 'Synchronization'.

Another influential activity in favour of efficiency of the JIT trend is to avoid unbalanced manufacturing time between each machining station and apply 'line balancing' to create a fluent process in which every stage uses same time and process same number of work pieces throughout production. Self-operating control system monitoring the unit machining and transportation is a powerful tool in line balancing. As it has been mentioned before, synchronization due to its ability to create a constant flow of work between different machining stages can be also influential in line balancing.

In some cases two different devices may couple together to work on one sort of product. It is possible that the operational capacity of the first device is greater than the second one. Conventionally the system would create a support buffer between the two; whereas in just in time the two devices are regarded as one system. The first device works exactly when the number of parts between two devices is less that the predetermined number and continues to work until the number reaches the default limit. This automated control is also effective on queuing time reduction.

Standardization of the machining operations is intended to raise three major benefits. Firstly, it minimizes the ongoing work. Secondly, it balances the production line via applying synchronization of the processes in the production cycle. And at last, standardization optimizes the production and increases the productivity.

Standardization is commonly determined in three steps namely as below:

- To calculate and plan the production cycle time
- Categorization of operations and dedicate necessary workforce
- To determine the necessary quality of the work in progress

To calculate the cycle time it is necessary to divide the total daily production time by required daily output, while there's is no margin dedicated to unit defects down time or idle time in the available daily production time.

As it has been mentioned before, the workforce in a just in time environment need to be multifunctional and carry multidisciplinary knowledge in various production related fields. In this system operators need to be able to work with various machines and perform many types of activities. These operators can help to minimize the inventory costs as when the machining finishes on one machine they can move it directly from one device to the next one. If the work load is heavy or for any reason an operator cannot perform the expected activity, other co-workers can help due to the fact that they know how to run different machinery (Schonberger, 1982) (Monden, 2011)

Apart from the queuing time, transportation is also a non value adding activity which occupies a large share of production time. In the Figure 2 .71 the two ways that the JIT suggest to reduce the redeploy time have been demonstrated. As it is shown one of them is the production layout which some details of it and the Ushaped production cells have been discussed before in this chapter.

Although unit production and transport optimizes the production process, nonetheless it may increase the occurrence part redeployment between work stations. In order to remove the negative impacts of it, modernized and fast transportation methods needed to be applied in production lines. Improvements has started by using conveyor belts(Japan Management Association, 1986) but modernization has not stopped since and in highly sophisticated production lines in companies such as the Porsche car factory they use automated robots to move parts between different production lines and work stations; they also move optional parts from shelves and deliver them to the assembly stations.

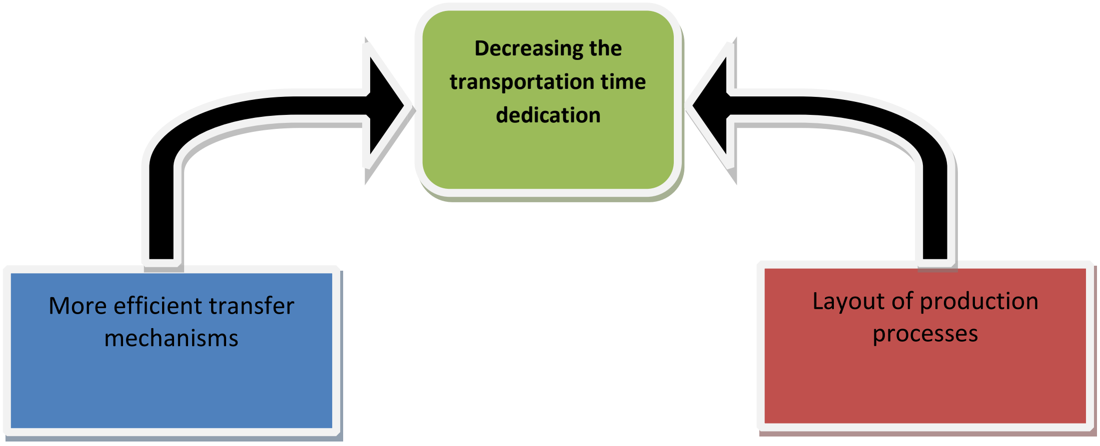


Figure 2 .71 Transportation time
Optimization of the transportation time (McMahon & Browne, 1998).

At last it is the processing time which is considered as an important component in production process. Although processing is a value adding activity in a production line, yet set up time a non value adding activity in traditional production systems considered as the prerequisite for processing. Trying to revolutionize processing, just in time strategies have offered a view toward the processing time due to the value based features. It tries to eliminate the set up time, redeployment time and queuing time because they do not add any value to the products and are just the necessities of the traditional production systems. Considering processing time as the only valuable member of the family of production activities, the JIT's focus is to make the most of this time and produce perfect artefacts in an optimized system. A just in time environment tries to use the last technological developments to increase efficiency and to recruit multi-skilled operators and to keep them updated by holding regular training sessions.

In general, it is in the desire for the best possible fabrication techniques performed by a group of expert operators that the chase for perfection in the just in time fabrication environment can be most vividly witnessed (McMahon & Browne, 1998).

2.9.7. 'World Class' manufacturing

The generation of 'World Class Manufacturing' is mainly owed to the just in time practice in American factories. They have also put an emphasize on the concept of 'persistent development' and keeping the workforce updated along with the unification of product design and process planning resulting in the simplification and optimization of complicated fabrication lines. The main features of world class manufacturing can be described as follows (Schonberger, 1986) (Schonberger, 1987) (Hayes, et al., 1988):

- To be competitive and focus on becoming the best amongst the other companies in the related industry
- Do not limit the competition to the time when the company reaches the top. In order to guarantee your success you need to develop faster than any other competitors. The measurement scale for success can be their success in the market.
- Absorb the best workforce. Keep them updated and train them regularly to adopt the latest technological and organizational improvements.
- Lead the technology. Train sophisticated technicians and engineers who are ultimately expert in design and fabrication. This way suppliers always seek for your advice to meet modify their service. This way you will be to one who shapes the industry and the market.
- Form a flexible system which is responsive to the changes of demands and supply chain. The more flexible you are the more successful you will be in the competition with other companies.
- Face the product and process developments with open arms. Upgrade your work environment to systems which are more efficient and productive. It is also good when opponents try to copy your products through reverse

engineering they realize they need to perform radical organizational changes in order to produce artefacts in the same standard as yours.

- Always work on development of your products. This way not only your products can match the current market needs but also While your opponents are busy to copy your product you work on your new product which is going to be in the market fast. So even if they can copy your product you are one step ahead of them.

The world class manufacturing is a western response to the lean production system which had been initiated in Japan. After the exponential growth of Toyota which made it the biggest car manufacturer in the world, the lean method which was based on the group oriented mentality of the Eastern Asian countries became popular in a large variety of industries. The Western companies were losing competition to the high volume of a more customer based strategy of the Eastern rivals. Therefore they initiated the Westernised method which could improve productivity and customer link and match the individualist culture of the Western societies (Black, 2008).

2.10. Latest trends in production

2.10.1. Introduction

The following chapter intends to demonstrate the necessity of information organization and feature based modelling of products through defining the idea of applying information organization. The quality of applying design data and involving them in models and their influence on manufacturing accompanied by modern communication methods, which connects the separate teams of a production project, will be discussed. In fact, it will be shown how the presence and quality of digital communication is becoming the bottleneck for many projects. In the next part of this chapter, the necessity of environmentally friendly production will be illustrated while the role of computer-aided procedures and modelling in such concepts will be emphasised. This definition of the necessity of environmental friendly production is followed by a discussion about how designing can be influential on this directional change and how companies need to change in order to adapt to this new environment.

Undoubtedly, the importance of these revolutionary changes which have been made in industries and our society by computers and digital technologies from the late 20th century on is comparable to the major impacts of the industrial revolution which had changed almost every aspect of peoples' lives in the mid 18th century. Although the emergence and development of digital technologies and devices is happening at a great pace, yet it is clear for all that it is only the beginning of changes, which even now are seen as radical in some fields, but eventually these will be greater and even more fundamental in the near future.

Ironically what has been called 'automobile' in 1672 is now fulfilling the term 'auto' when cars and their control and traffic management systems are being designed by companies such as 'Google' and 'Siemens' as IT and communication technology companies and many other companies with different fields of work [Figure 2 .72](Wohllaib, 2007) (VINCENT, 2013); 'Smart cars' now can move along roads safely and reach destinations without humans being directly involved in operating, directing and controlling by using pedals, levers and wheels. Instead of physical tools, digital technologies such as satellite navigation, sensors, and feedback system control are now capable of deriving 'automobile'. Digitally controlled cars are only one example out of millions of innovations which are being developed every day to move us towards a fully digital integrated lifestyle.

Figure 2 .72 The Google car

A picture showing the interior of a 'Google Car'. These cars are also known as robot cars are capable of driving on roads and take passengers to their desired destinations. They use satellite, sensors and feedback systems to operate. The project is currently under development. Picture (Anorak, 2010).

IT developments have also significantly changed the way of peoples' connectivity and have created a global market and supply system where collecting correct, detailed and on time information is a key factor in the success of companies. Other concerns of the work of industries relate to the growth of business and the rise of market demands in addition to limited natural resources and climatic changes that have negative influences on humans' lives which consequently give rise to concerns about the future.

2.10.2. Organization of information groups

There are many teams involved in every project; even though they are connected within a modern framework, each team should be aware of the work of the other groups involved in the project so as to present their work in a manner that would be compatible with the other teams' work, yet the focus of each team's specialty remain on a certain aspect of the product. Consequently there can be a variety of digital devices and digital databases with each one related to certain teams or features of the project. In a modern environment, where all different types of design and production information is being generated it is necessary to benefit from a PDM application [Product Data Management] capable of organizing all sorts of different databases in different teams containing information in various formats and make them accessible for other groups that need to develop their work based on information, provided by other teams. Examples of such systems in the realm of building design and construction can be seen in chapter three where comprehensive and central models of the buildings and their embedded data paves the design and production way and provide assistance for project planning and management.

Such systems may be involved in many aspects of the work in different industries. For instance, a commonly noted feedback from users may trigger an investigation by the QC department that runs studies about customers' comments and as a result they may inform the design team about the necessary changes in their approach to the product. This change can cause changes in design and subsequently fabrication strategies and details. This cycle of communication in fact shows the value of a central integrated database to link different departments which are involved in production.

To define a product data management application one way is to group its activities into two distinct areas of impact namely users and utilities respectively.

The first field comprises (Crnkovic, et al., 2003):

- information organization which directs the databases, information safety, accessibility of the data and so on
- Definition of the jobs and procedures which draws the perspective of work, allocation of workforce and plans the procedures.
- Describing the details and features of the final artefact.
- Categorization of information in order to facilitate the access and to not miss any detail
- Set up project criteria and agenda to plan for access to necessary resources or anticipate work stages and so on.

On the other hand the second field of PDM tries to (Crnkovic, et al., 2003):

- Build a strong communication link between all departments and also provide communication with entities out of the company which can be influential on the production process.
- To build a strong platform for data exchange between different applications, teams, stages of the project and machinery and devices.
- To transform the information format in order that it might become useable in different devices or by different teams to process the information and develop some aspect of project.
- To provide visual representations of the data to be analysed by engineers or discussed with users.
- To manage the organization of the information system. Basically to control the input and output and/or accessibility or may be data mirroring to support the system against possible data loss

2.10.3. Information based models

The product data management applications are the extension of CAD systems that are capable of modelling physical form of artefacts. In fact PDM computer applications are advanced production tools which acquire their sophistication from the contribution of computer applications responsible for volumetric modelling, production organization and administration, evaluation and information structure planning and management that facilitates the contribution of discrete applications and systems in one unified production environment. It can be said that the ultimate perfection of the file to factory technology or computer aided design and manufacturing with the current perspective is to form a database for every single product which contains all the product design, manufacturing, supply, distribution, life cycle and disposal information from inception. Such a database that represents all aspects of an artefact is also known as the product model. The Figure 2 .73 is a schematic representation of the cited models which also demonstrates the common aspects of an artefact which is usually needed to be included in such models (Sendler & Wawer, 2008).

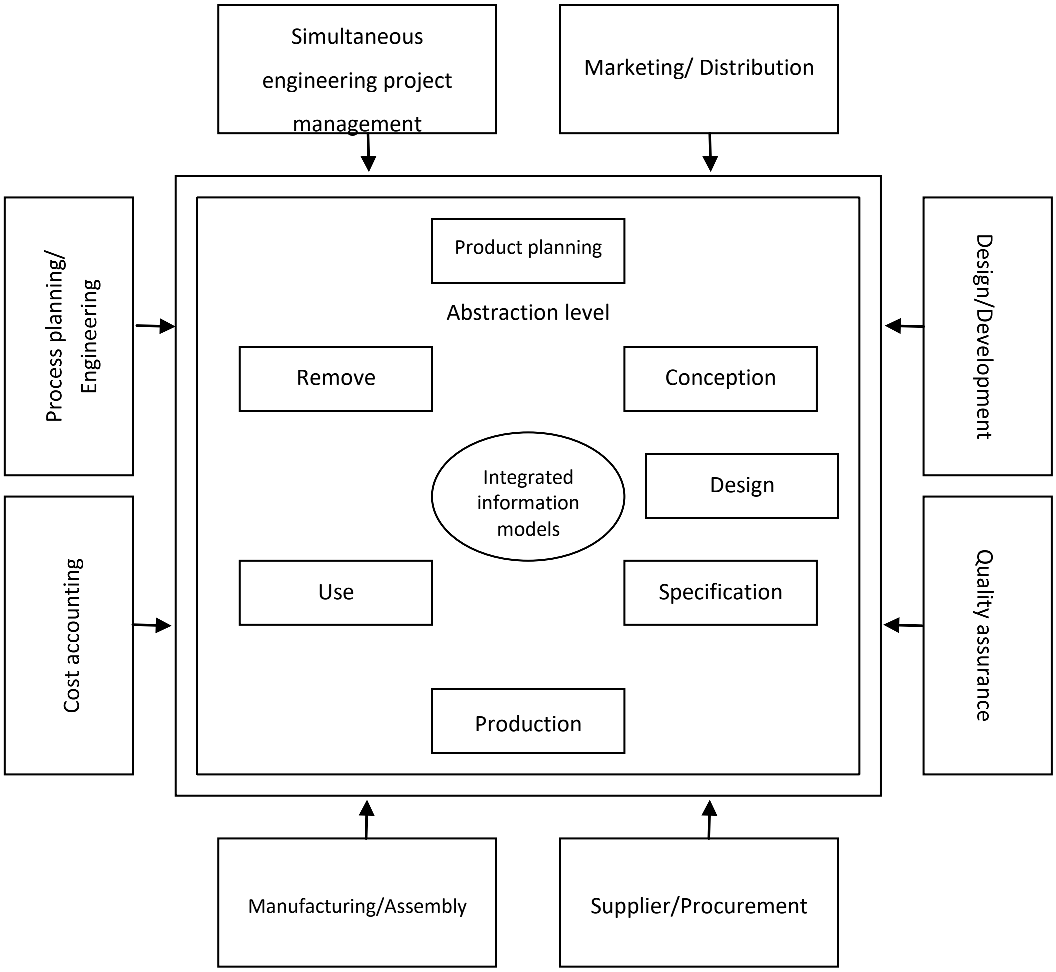


Figure 2.73 Product model

A schematic product model (Krause, et al., 1993).

As has been mentioned, currently the creation of comprehensive information based models of projects can be regarded as an ultimate goal in production industries. In building architecture, 'BIM' or 'building information modelling' plays the role of that thorough such a model. This system shares numerous features with other similar models which may be used in other industries. Basically their structures are largely similar but the information type will be different depending to the intended final product. BIM systems are going to be described in the chapter 2.11.

2.10.4. Component based product models

One of the significant features of every product model is that they consist of detailed information. Models may define physical features of artefacts and a hierarchy of the components' assembly sequence in their pre-planned places to make the final products and also may describe every single physical relationship of individual components. This family of information is known as the bill of materials or BOM playing a key role in projects' development especially in regard to the generation of product models. In an industrial project, if designers and planners need to establish the way components actually physically join, then they need to create assembly models which are considered as a higher level of organizational tool compared to only the combination of bill of material data with a model which shows the physical form and the geometry of artefacts. The latter is only capable of showing visual features of assembly and joints and do not cover the quality of componential merges and joints.

Basically the major elements of an assembly model are the illustration of components' joints accompanied by depiction of details about the quality and hierarchy of individual parts merging together. Obviously there are going to be limits that form and constraint the assembly process and therefore the assembly models which are known as 'mating relationships'.

These descriptive models of component relationships can be grouped into five major categories. 'Part-of' shows the hierarchical relationship between parts, assemblies and subassemblies; ‘structuring relations’ also known as ‘SRs’ shows the relationships between two individual components in formation of artefacts. ‘Degrees of freedom’ or ‘DOF’ which determines the possible moves in the assembly line which suit the intended product; ‘motion constraints’ also known as ‘Lts’, reviews the DOF, analyze and eliminate defective motions; and finally ‘Fits’ which test the assembly plan against the dimensional limits (Shah & Rogers, 1993).

Figure 2 .74 illustrates an assembly process organization described in the Shan and Rogers book on assembly modelling.

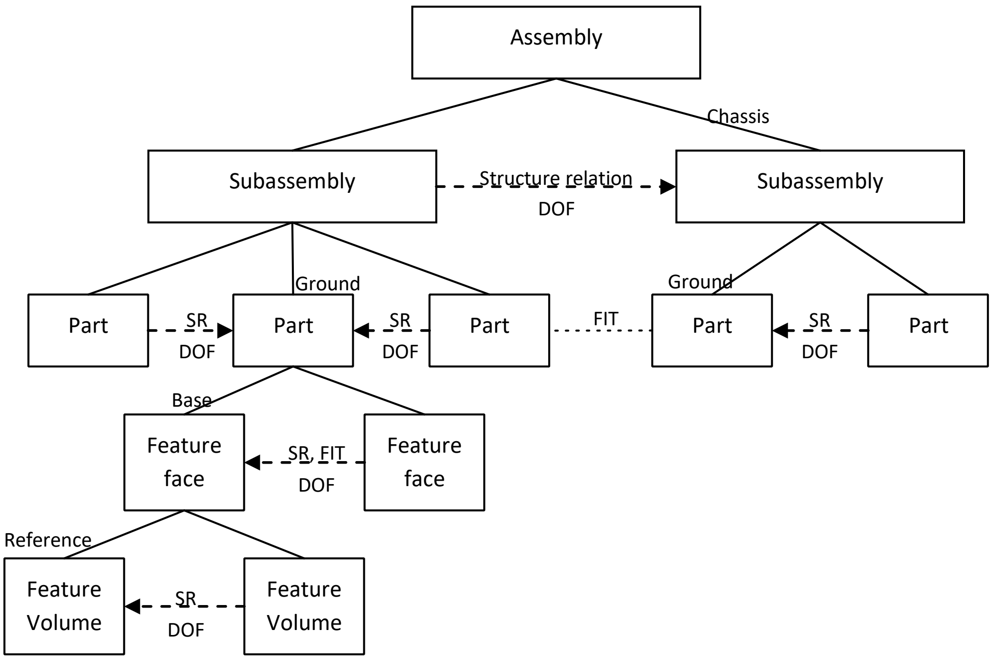


Figure 2 .74 Assembly links

Hierarchy of assembly relationships (Shah & Rogers, 1993).

2.10.5. The World Wide Web

As has been mentioned before, the outstanding advantage of the product data management technology is the ability to provide seamless bedding for strong connection between discrete groups participating in production projects. By the end of the 20th century, enough technological infrastructures became available to create networks of computers to share data between them. At this time Stanford established the first web server in the America. It has been used to transfer digital data. Two decades after that ground breaking innovation, the versatility of internet applications have become even more prominent. Using this global data network enabled companies to have direct contact with each other and even with their users. Nowadays, not only can companies receive users' feedback through the net to improve their services but also they can receive customized orders directly from their clients. The internet has also facilitated the internal connection between various sections of factories to the level that the ordering, processing, planning, manufacturing and preparation for delivery procedures are becoming an automated cycle of works. Using information technology and the internet has opened new doors in front of industries. Now they can have collaboration with unlimited consultants, contractors, subcontractors, suppliers and users all around the world regardless of the geographical distance (Krar & Gill, 2003).

2.10.6. Virtual teams

It can be witnessed that social networking services such as 'facebook' have brought people together and now provides a platform for their social interaction which has become part of their daily lives. The same ideas exist in industrial environments where the internet has become an inseparable part of their systems as a data exchange tool. The collection of all devices, applications and facilities in addition to data network which manages the group works and process is discussed in the realm of 'computer supported cooperative work' or 'CSCW'. Influences of the CSCW systems in production process can be divided into four main categories.

The first category is dedicated to the field of communications where computers can make it easier, faster, and more accurate and involves multimedia data packs which provide visual illustrations of data or closer interpersonal connection through virtual conferences so providing space for discussion, oral and visual contact. In the next category there are facilities which provide 'shared work space' where co-workers in diverse locations can work together at the same time and can share their own view points, for instance on a common computer display. Sharing can also happen in the case of databases which form the next group. 'Shared data' enables all the users to have access to the same database and use the information needed and share their work with others due to their level of access classification. Another group of useful features function throughout the production process is the ones that facilitate 'group work and assistance'. Such functions provide facilities for production departments to divide their work in a predetermined fashion or to share data with consultants. This way they get involved in related stage of projects and collaborate with project teams (Wilson, 1991).

2.10.7. Green fabrication

Due to growing concerns about the emission of the greenhouse gasses, global warming, limited resources, etc. the theories and practices of green and nature friendly production are rapidly changing the mainstream of industries.

Partly based on governmental regulations and partly because of futuristic humane reasons, green production tends to plan not only for the production period to be environmental friendly but also the whole product lifecycle to be green and cause minimum harm to the surrounding environment. For instance, a production organization can comprise the management of product design, manufacturing planning, supply chain arrangement, delivery and sales, use and lifetime services as well as discard and recycling of the product (Alting, et al., 1993).

Essentially the concept of Green fabrication / Green Manufacturing is comprised of two key functions. First is to produce green products. In this regard, Green fabrication systems focus on the creation of products which are used in renewable energy system or have an environmentally sustainable lifecycle. The second approach in this concept is to transform production plants and systems to run production processes in a green manner where detrimental effects to the surrounding environment are reduced to minimum (Ni-BinChang, 2011).

Apparently many companies take the disposal of used products serious; amongst them those producing electronic devices possess the lions share. Companies such as

'Hewlett Packard' [HP] or 'British Telecom' [BT] have recruited a large number of staff to process tons of electronic dumps each year and seek to recycle the useful parts. Mentioning other examples, many prestigious car factories around the world that make expensive cars have developed workshops that refurbish their old models to prepare them for reuse.

As it can be seen in the Figure 2 .75 there will be a dramatic contrast between the current theme of production and what is demonstrated as an anticipation of the production approaches in the near future. Currently, manufacturers intend to produce green products and avoid using elements which can be harmful for the environment through sustainable processes. The modernised generation of fabrication systems have a more holistic view toward the production and product lifecycle. Such trends bring more liability for companies as they are responsible for their products during their lifecycle and also over the disposal and recycle period. A schematic definition of these systems is presented in the Figure 2 .76.

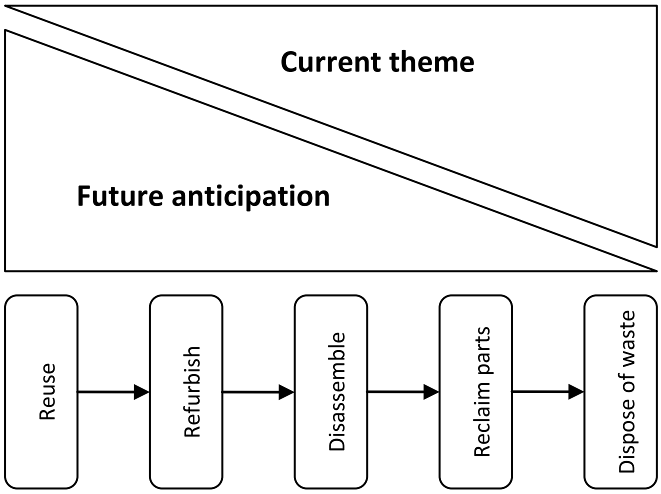


Figure 2 .75 Future systems

Contrast between current production theme and future systems (Browne, 1995).

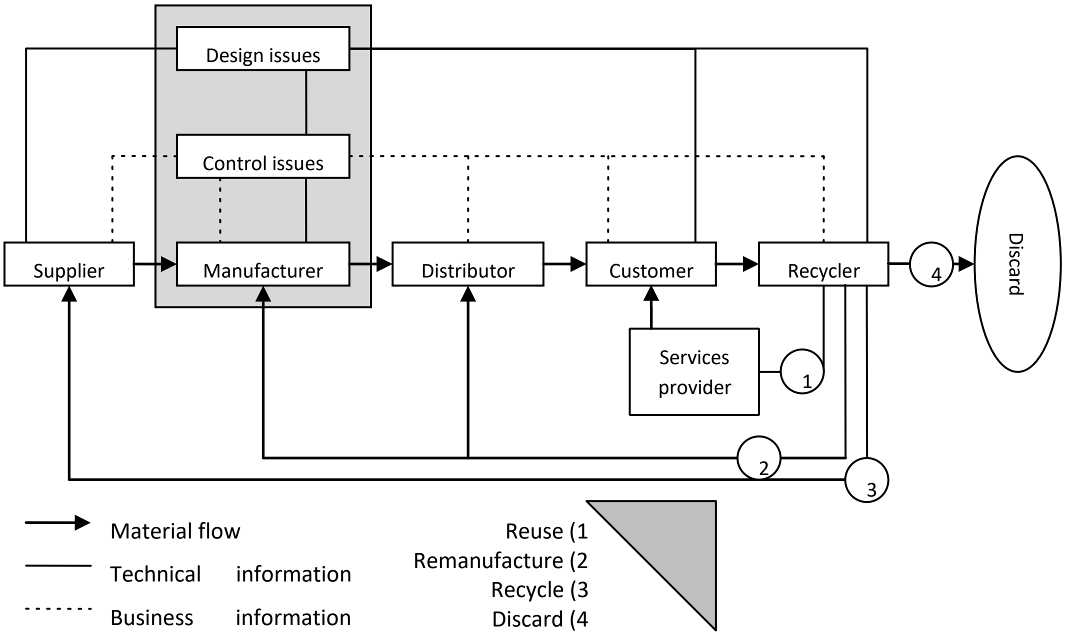


Figure 2 .76 Production systems
Futuristic anticipation of production systems (McMahon & Browne, 1998).

2.10.8. Sustainable projects

It has been a while since designers first regarded environmentally efficient factors as an advantage in their works. Recently they added sustainable features to their criteria. ‘Design for disassembly’ or ‘DFD’ and ‘design for sustainability’ or ‘DFS’ is in the relatively newer group of design strategies. Although they may be related to each other or in many cases complete one another, but it is essential to bear in mind their differences. In design for disassembly during the design phase, the designer considers the fact that the end product’s parts should require to be effortlessly separable. Consequently products can be easily refurbished and reused by part replacement or their individual constitutive parts can be used to make other newer products or as spare parts for other operational products of the same model. Apart from the feasibility of easy disassembly, the process has to be efficient and financially affordable for companies.

The impacts of DFS are more consistent over a longer time span and the concept includes a variety of strategies and techniques. A definition of the concept is presented below:

"*The measure of man's technical progress is given by the fact that the pyramids of Egypt lasted for 5000 years, the castles of the middle Ages for 500 years, the machines of the industrial revolution for 50 years, while a modern car lasts only five. It is astonishing to realise that while economic growth has been made possible largely by technological advantages, these achievements are themselves only possible because of a quantitative sufficiency of artefacts with ever shorter lifetimes. That is, technological progress and advanced manufacturing techniques have only helped to shorten the lives of artefacts*" (Tomiyama, 1991).

He also describes the efforts after the era of mass production to extend the lifespan of products and increase the value of artefacts as:

"*Of course, it is impossible to make something with an infinite lifetime and even if it were possible, an infinite lifetime would be wasteful. Instead, we are talking about an artefact that can be progressively developed into a system, a concept in which the manufacturing industry grows based on demands for renewals and maintenance*" (Tomiyama, 1991).

In the current climate where many industries are computer integrated or becoming one and use digital technology to deliver their services and products an interesting question would be that if these relatively new technologies and methods could make green Manufacturing systems and green products. More specified views towards applied strategies in sustainable architectural projects in a computer integrated environment are demonstrated later in chapters 3.4, 3.5, 3.6 and 3.7.

2.11. Building Information Modelling

2.11.1. Introduction

Forming a database containing all the required data to represent building information throughout the project's process starting from concepts and design right through production and construction with added project management inputs has been the subject of many researches and computer application developments for almost four decades(Eastman, 1999).

Traditionally, production of the necessary data to transit a project from the design phase to the construction site was done manually as a result of the collaboration between different groups of experts, each mastering a limited domain. When computers appeared in the realm of building construction, activities such as 2D drafting, structural estimation, bills of materials production and project management scheduling were done easier, faster and more precisely. Software vendors introduced discrete applications so that each of them could be used to produce certain groups of building data separately; yet the ultimate goal in this field appeared to be the creation of an integrated organization to contain all the building related activities in one virtual place which can provide better communication between different stakeholders (Howard & Björk, 2008).

The term 'Building Information Modelling' or 'BIM' is referring to a relatively new system of design and documentation in regard of design and construction data. In this system all involved sectors of project are linked together through a comprehensive database. BIM is one of the strongest tools in modern production systems, and among them being File to Factory technology, which facilitates the direct connection between designers, their consultants, fabricators and the product users.

2.11.2. A general view

In the business of design, engineering and construction, BIM is sometimes regarded as a class of software, whereas this is actually a concept which contains a wide spectrum of applications and organizations. In fact a Building Information Modelling system applies digital software to conduct the flow of work and associated information. Sometimes there is a misunderstanding between CAD applications and BIM systems. One of the most important differences is in the nature of the two. CAD applications are graphic oriented and which deal with shapes, lines, symbols and colours that imply conventional meanings to the users as visualisation tools and do not necessarily carry any real life features; whereas in BIM models, as an object oriented system, visualization is only one of the services accompanied by many other layers of building information which all add real life features such as material layers, weight, colour, structural properties and many others which relate to each object in the model as well as the project management data for the whole project. In fact, CAD applications could be regarded as a revolution in drafting meaning that while BIM systems in their comprehensive use can play a pioneering role in documentation and communication between different groups of a project. Consequently the systematic evolution of CAD towards BIM could be seen as a transition from solely visual representation to an exclusive and comprehensive simulation (Succar, 2009).

A BIM model of a project is a virtual replica which is structured by parameters. It contains all the design information and construction details simulating the project as in real life. In addition, the time frame of every stage's termination is included in the model which describes the work flow and enables different groups of the project to have concurrent progress in their work. Providing all of these services have made BIM models distinct from ordinary 2D or 3D CAD models. In this integrated system, any change in details made by each sector is seamlessly and simultaneously influential on the work of other groups and provides a real-time description of the current condition of the project and the task plan of each party. Based on the boundaries of BIM and CAD's field of effectiveness and the current market which demands for more, customized and faster produced artefacts, BIM seems to be a big step forward since using CAD applications in design and production equals the modernized way of producing with traditional techniques but applying modern tools suggesting recurring design/planning, assessment and redesign/plan; whereas BIM system implies continuous improvement and concurrent procedures(Weygant, 2011).

The analytical information, provided by BIM software facilitates the process of designing, project planning, production and/or construction. This tool helps the final product to be delivered on time, on budget and carrying the needed qualities. These objectives are gained by an estimation of the procedures' time, bills of quantities and simulation of the design proposal and the building's real life performance (Krygiel & Nies, 2008).

2.11.3. The necessity of BIM

It can be witnessed that BIM's position just as a tool has been raised to that of an inseparable component in the fulfilment of many construction projects. Before describing the details of BIM systems it is worth having a look at its place in current projects' lifetime and the reasons why it has reached this level of importance in the organization of construction jobs.

Numerous demands of users and the ambitions of designers have made buildings and the procedures of construction extremely complicated over the last century. Many more services are included in today's buildings compared to those that were constructed just decades ago. The services such as electricity, telecommunication and data, air conditioning systems, underground car parks and security systems etc., have added many new layers to the design and construction process of any buildings. All of these new attachments and associated complexity need more detail and consequently more records providing the necessary design information. More information equals more configuration time and without any system of classification which provides easy access, due to the growing complexity of design, time consumption grows exponentially. Sophistication in form and additional systems and intensification in large scale projects cost money and time for designers, contractors, fabricators and subsequently their clients. Therefore the performance of systems and final products faced a dramatic decline and increasing waste. The huge amount of information and design documentation needed a system of organization. In addition the complications of design required all parties which are involved in a project to have a closer interaction in their turn to result in a seamless strategy to complete the project with minimal waste and defects (Krygiel & Nies, 2008).

2.11.4. BIM in action

For several decades designers have used drawings as an image of that which would be built later. These drawings, either made by hand or using digital means, only carry various types of lines with different thicknesses or colour to represent the whole building or just simply a component of it. These properties have made each project document carry only a limited amount of information. Considering the complexity of design and face to face connection between designers and constructors it was feasible to construct buildings several decades ago; still, just using traditional methods to run projects caused many problems. There has always been at least a few misunderstandings between designers and constructors due to the lack of specific construction details which in most cases caused the result to be unexpectedly different from what which had been designed. As another example, in almost all projects, designs had to be changed several times during the execution because the design proposal had not been actually feasible. Sometimes an error such as this may require all drawings to be changed. In a traditional system this process needs a considerably long period of time to revise all plans and calculations which will subsequently increase the costs and time consumption of all other stages of project (McMahon & Browne, 1998).

BIM systems are artefacts of the current theme in construction projects. They allow the attachment of layers with practical functions to the design proposals. They provide different level of access to information for different groups. Access to data fortifies the necessary communication which can provide a time plan for individuals to help increase productivity and support their work with necessary details (Howard & Björk, 2008).

In a BIM system all of the details are extracted from a BIM model. This inclusive model is an example of an intelligent system. When the design group works on a plan, any influence caused by changes in each component of a building is distributed amongst all other components and will apply automatically and concurrently. For example, alternations in plans will be influential on all elevations and sections, structure, bills of materials and schedule as they have been programmed by parameters. Basically it does not matter where the changes are made; they are affective on all necessary components. It is not needed to provide annotations or draw additional section plans to imply details, the model carries all the properties of the intended finished product and information could be extracted from the model (Smith & Tardif, 2012).

Regarding the definition of lean construction and BIM systems, it could be said that BIM systems can be the key element of the lean concept in construction. Providing the client-designer-contractor interface, where all parties can collaborate and contribute their share to the project and facilitating processes which can develop simultaneously. In such an environment, waste has been reduced systematically and better communication can guarantee that buildings and construction products develop and finalize as they should be, nothing more or less than what is expected by clients and planned by designers (Aziz, 2016).

2.11.5. Advancements through BIM

In a BIM system simultaneous and continual modification is mostly preferable. Users believe in gradual improvement which provides stability in process and ultimate perfection, rather than making dramatic changes which may have destructive effects on plans and schedules.

One of the most regarded benefits of BIM method is the transition from 2D representational drawings toward three dimensional simulation models which carry all required characteristics of the final product, sequence of work, time frame and assembly details. In addition a BIM model can simulate and measure the environmental impacts of projects and vice versa (Krygiel & Nies, 2008).

Such models provide large amount of information about products and components and by categorizing those help saves time and assists in arranging the subsequent procedures. Benefiting from several sophisticated extra layers of data enables systems to operate seamlessly and the results will be highly precise. It can be as accurate as an exact match for design proposals as well as the real life project (Eastman, et al., 2011).

Last but not least is optimization. Well-organized processes measured quantities comprehensively demonstrated assembly methods and details of components, and well defined relationships between different stakeholders can make this system efficient and reduce waste in time, material and workforce (Weygant, 2011).

2.11.6. Systematic change

There have been dramatic changes in the design and construction phases in BIM methodology compared to what rules traditional systems. As has been mentioned before, the most recent theme of work needs and supports a gradual and concurrent modification of the design. To express the benefits of the new organization it is helpful to study the traditional flow of work [Figure 2 .77 Traditional flow of work in construction industry].

- The designer gathers necessary data from site and customers to form his basic concepts.
- The designer finishes the design and makes the 2-D drawings and sends them to several consultants, each develop the design in one aspect. [For example: electricity, mechanical, structure ...]
- Consultants do their research and design, based on their specialty and prepare the new drawings, which sometimes inherit some unexpected changes imposed by the designers, to make the new layer of data that add a service into buildings' functions.
- Consultants send back the new drawings to the Architect. The designer analyzes different drawings trying to find a way to keep the characteristics of space and form in the design and find a way to adjust different systems in order to provide new drawings for the project capable of including all required

systems. Sometimes the designer may need to send the drawings back to one or more consultants to refine their design because they conflict with other services.

- After putting all services in one system, the designer creates new drawings and sends them to the contractor. The contractor then divides the project and confers each part to different subcontractor to check the feasibility of construction and plan construction of every single component. They make drawings, demonstrating the construction details. In some cases making a few parts is not feasible or the design needs some changes to make it constructible. In this case they refer back to the designer and all the work for those components to design and create drawings should be done from the first step and if the components are key elements on the building's design, it is not so disruptive that all of the procedures have to be redone for the whole design proposal (Tunstall, 2006).

It should be noted that in all of the above mentioned traditional processes, there's always the risk of miscommunication and misunderstanding between different groups; whereas a BIM system can facilitate communication and reduce the design errors by connecting various parties. It also improves the timescale by decreasing the amount of unnecessary documentation processes as well as on estimation, checking and re-checking. On the other hand, groups have more time to focus on design and planning rather than spending time to redraw and checking for possible errors caused by miscommunication.

As we expect from a BIM methodology (Krygiel & Nies, 2008):

- Architect is in direct connection with consultants and contractors. In fact they collaborate from inception to conclusion and creation of project model.
- After the model is created, it is time for subcontractors and construction teams to do their part and fabricate components and develop on site works.
- Details of site work and progression and completion of various parts of the building can be shared with all of the groups.

- Clients can have access to this model to plan their works. Such a model can be useful even after the submission of finished building to the owner. The owner can use it for the building maintenance and further developments and possible additional buildings.

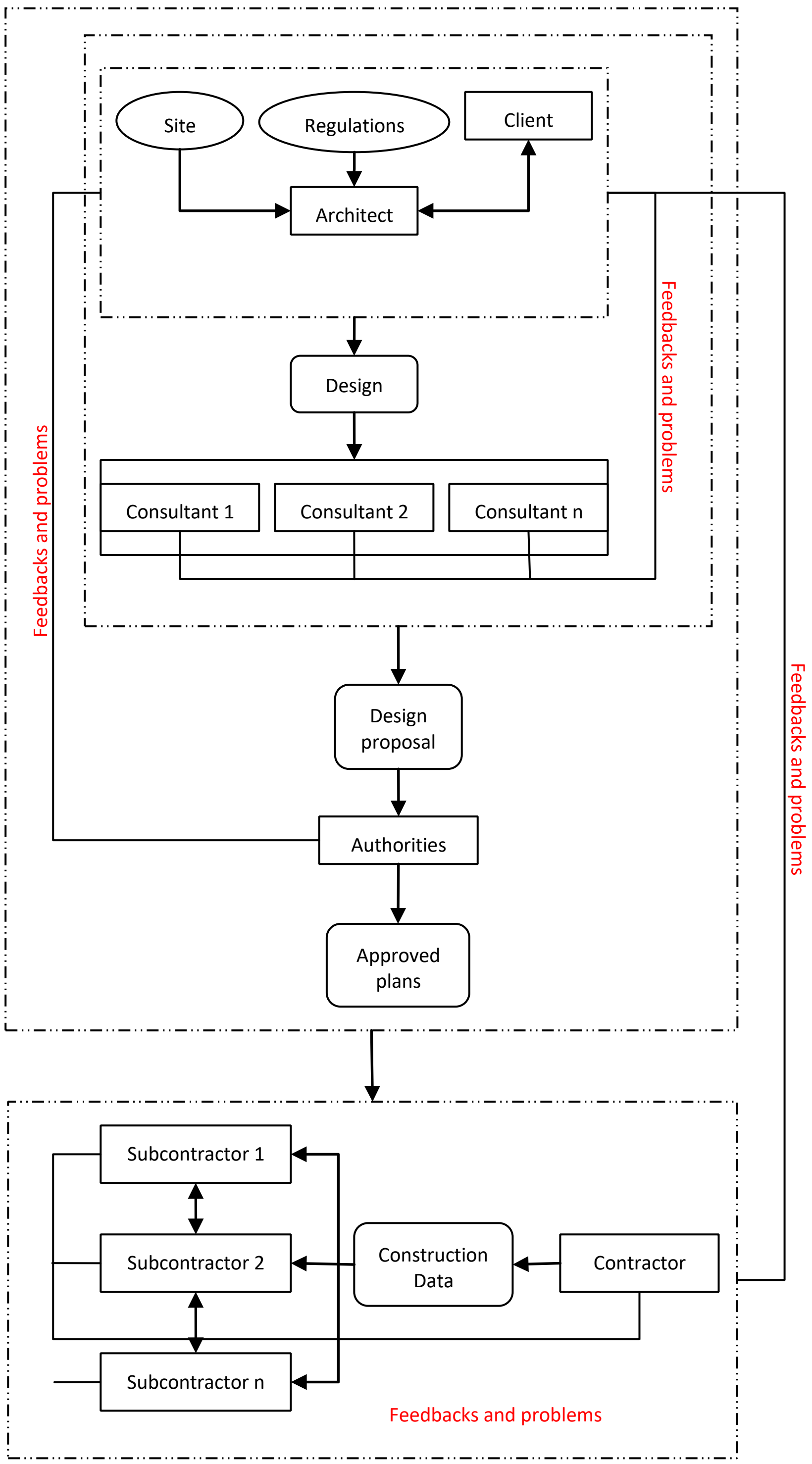


Figure 2 .77 Traditional flow of work in construction industry

Based on the general construction regulations, the clients' demands and designers' intentions, several specialities could be involved to create a building model. Systems such as structure, lighting, mechanical, etc. can dictate the direction of design. In a modern organization, some systems now have clearer connection with each other and affect their work. For example natural lighting systems can be influential on direction, form and subsequently the structure of the building (Krygiel & Nies, 2008).

2.11.7. Advantages of BIM systems

The construction industry had initiated BIM as a tool for ease of documentation. As the target users of this innovation, designers and constructors have benefited from this system even more than what they expected from it.

Almost all of the subsequently added functions to the system are resulting from the new means of real time simulation and digital realization of designs. As has been described, this model uses the enhanced power of computers so as to provide different views of the building, tables of materials or schedules and so on all at the press of a key. Basically every component of the model can be measured or quantified due to the parametric description of it. The impacts of BIM are not limited to documentation and design; it has a strong influence in the construction process and buildings' lifetime.

In order to emphasize the beneficiary factors of adopting the BIMs McGraw-Hill Construction Company based in the United States has released a series of data in 2009. As has been demonstrated in

Figure 2 .78 they documented the hierarchy of the effective factors on the adoption of the BIM by the construction companies of the future.

Remarkably, buildings have become exponentially more complicated over recent decades. If half a century ago we needed 50 sheets of drawings in order to build a building, with added services and details we now need three times more documents to execute the process. In a BIM system since all the data is being gathered in a single model the documentation process is almost done automatically. Just imagine how time consuming it would be to draw all the documents manually and if some changes occur, to check and correct all documents one by one (Eastman, et al., 2011).

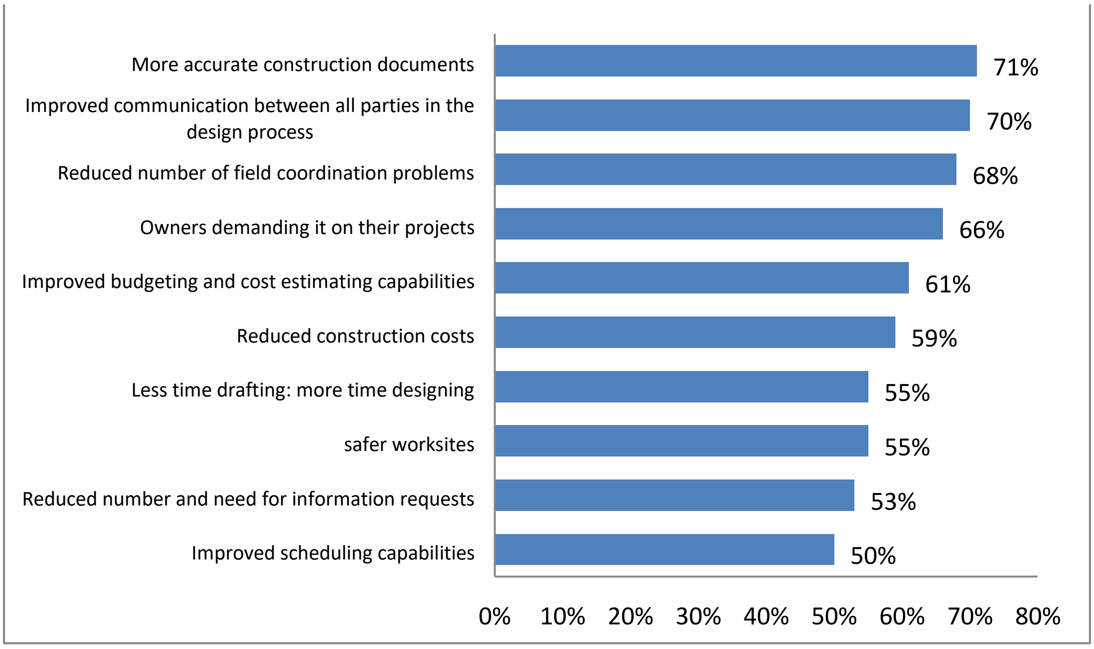


Figure 2 .78 BIM

The hierarchical presentation of the inflectional factors on the adoption of BIM by construction companies in future. Data (McGraw-Hill Construction, 2009).

A BIM based project benefits from a comprehensive model which contains all the various aspects of the building which helps us have a good understanding about the design. Three-dimensional models provide virtual realisation (visualization) for designers to help develop design work and to present their work to other stakeholders and service providers. Such a model also could be used for rapid prototyping. A comprehensive base of knowledge particularly in large scale projects gathering many different groups and in diverse and changing project teams is critical as data can be passed from one user to another and the success of the project is related to the systems work rather than the continual presence of individuals (Howard & Björk, 2008).

Working with a comprehensive model may also help us have a good understanding of the design we make. Three-dimensional models provide virtual realisation (visualization) for designers to develop design work and to present their work to other stakeholders and service providers. Bills of materials can be added as an information layer to the BIM model. Through that, not only can a visual representation of the design be produced, but also engineering calculations, cost estimation, construction hierarchy, schedules and many other layers of necessary data can be added to the model (Weygant, 2011).

2.11.8. BIM and challenges

As has been mentioned before, IT developers have introduced object oriented BIM systems in order to defeat the shortcomings of graphics oriented CAD applications. BIMs provide a platform for simulation, documentation and communication. They also offer the automation of design and documentation through pre-defined packages of data which exist in the system. Such an approach is popularly used in computer application development business (Martin & Odell, 1997).

In the modern world most of our daily activities which may affect others are framed by regulations and rules in order to control the consequent impacts. Design and production are amongst those activities and services that must follow numerous regulations and guidelines (also known as standards) which are protected by law and responsible organizations. Such rules that are definite and should be followed by every person and organization are known as the ‘official’ or ‘de jure’ standards. On the other hand, some standards exist that are universally accepted by the major players in a particular industry. These rules known as ‘de facto’ standards and can be regarded as a common language connecting separate parties together. These frameworks are not assigned by law but by the industry and in order to be able to work everybody should know that language (McIntyre, 1997)(Eastman, et al., 2011). Being a designer in the building construction business initially enforces us to realize that constraints form most parts of our design and it is not just the manmade rules but also the natural and environmental forces. Generally, the more the standards and rules we include in our design then the less the variety of products we are going to have.

In the building construction industry, we subconsciously suggest a level of standardisation applicable to elements and processes. When we discuss the essentials of the modern market such as automation, optimization, communication and collaborative systems of design and production is essential to define the existence of a standard language (Howard & Björk, 2008).

In a BIM environment objects are to be defined by their real life properties. Allowing users to add real building features to each object in their design; currently they can choose from the classes of material, shapes and object profiles which are predefined in the database (Weygant, 2011).

Although it appears that theoretically Building Information Modelling is a huge leap forward in terms of an improvement in building construction, yet after four decades of an IT presence in the industry, companies do not tend to adopt the systems fully in their practices. One of the key reasons now is the complicated user interface of the BIM applications which calls for staff training. The costs are also considerable as a large amount of money requires be paid for training, licensing and competent computer hardware. Nevertheless most of the experts considered the influence of high level of standardisation on the creativity of their work as the main obstacle. The BIM de facto standards should be designed in such a way so to be compatible with the normal flow of work and information; nevertheless seemingly these standards can overlook some vital factors. Standards must be applied to a level which does not cause any flaw in the innovative aspects of the work.

In an extreme case the ultimate result of the development of BIMs can be the creation of a comprehensive system containing all the standards and rules that can offer the right solution for any scenario. It is foreseeable that by considering today's advancements in the realm of computers and data gathering such a concept is possible, if not now at least in the very close future. The question here is that if we want to standardize our living spaces and the built environment to the point that machines can design buildings for us, or how much influence do we allow the quest for maximum efficiency and productivity to influence the shape and the quality of our buildings?

Howard and Björk in their research on BIM state that: "*There are benefits from applying BIMs to industrialised buildings. Some changes can be: integrating design and specification, automating regulations and creating a collaborative umbrella".* In the following parts they claim that: *"The idealistic goal of BIM has been to provide a single building model capable of being used throughout the process".* And finally add that: *"National groups have often been successful in implementing modest standards such as those for CAD layers, but international implementations need to be tailored for local cultures and conditions*" (Howard & Björk, 2008).

One of the barriers against the progression of BIM use in architectural projects could be the lack of knowledge about the benefits of such a system and related computer applications. So far, most of the focus has been on the modelling part of the BIM systems; whereas the main element of these systems could be the information (Kumar, 2015).

Lack of client demand could also be named as one of the main reasons that have caused BIM systems not to be applied in more construction projects. The figure below demonstrates how companies are mostly interested to use BIM when it is asked by their clients.

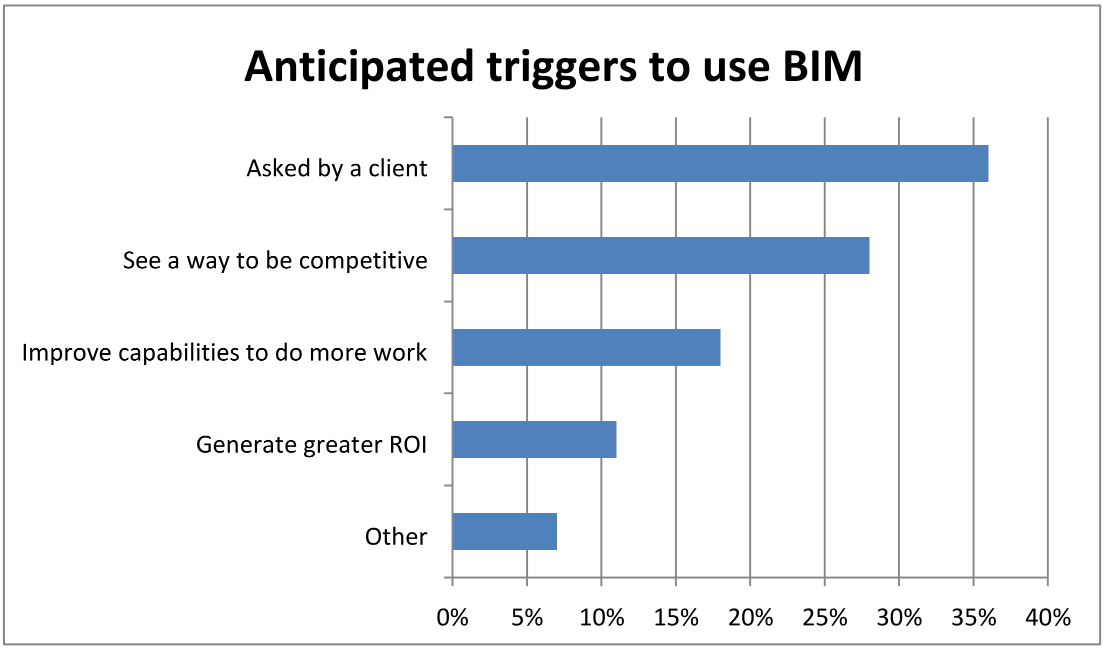


Figure 2.79 Triggers to use BIM
Picture (McGraw-Hill Construction, 2009)

Whilst Scandinavian countries and US began to promote BIM and speed up the use of systems in order to make the construction industry and the built environment greener and more efficient the UK hasn't been up to the same pace. More than 50 percent of the American and Scandinavian contractors have adopted the new system while in the UK only 24% of similar companies have achieved that. In order to increase the number of BIM integrated construction projects, the British government set a rule which came into force from 2016. Based on this rule all public projects started from this year and costing more than 5 million pounds must use BIM (Watt, 2012) (Klettner, 2011).

Research has shown that most of the actors in the construction industry believe that BIM will have a big influence on their work in the future. Not only the use of such systems is growing amongst contractors but also the speed of this growth is increasing exponentially (Kumar, 2015). Based on a survey ran by McGraw Hill construction division, the global growth rate in using BIM from 28% in 2007 has increased to 48% in 2009 (McGraw-Hill Construction, 2009).

2.12. Summary

Throughout chapter two, the first aim was to establish the context of the technology through an investigation of the state of the art in Computer Aided Design; this has been sequenced in part chronologically and in part functionally. The investigation continues through Computer Aided Manufacturing, through Process Control and the Organisation of Work within a digitally integrated production industry. The outcome is an understanding of the possible potential for improvements in workflow and product quality.

To summarise the investigations which have been presented in 'chapter two' these are as follows. The chapter starts with a brief exploration of the diversity, penetration and capabilities of CAD. Of particular note is how systems were introduced by high value, heavily capitalised industries but quickly became more widely available to the general industry sector. In parallel to the advances in the adoption of CAD it has been shown that there is also a growing advance in associated CAM technology. It was found that the capabilities of CAM are delivered through NC and the improvements of the 'Numeric Control' systems and devices as mechanical and digital devices have been described.

The next section explored the basic relationship between design process planning and production and investigated the concept of standardised paradigms and procedures which result in the evolution of standard language and concepts of the methodical design approach. As a result it can be seen that the definition of standard design models has allowed the market to identify and refine aspects of the process in the pursuit of economies and efficiency. For example, a key aspect to a design model is the system of representation – for the purpose of design development, documentation and ultimately communication. In every production process there should be a strong and mutual relationship between the design model (i.e. technical drawing) and the design and production process, where increased complexity has required the ability to move from a linear design model to a concurrent approach enabling input from a more diverse project team and noting the evolution of the accepted design models. On the other hand it has been found that complex projects require methods to expand the capabilities of the design model and its ability to contain greater amounts of data. Ultimately, it has been shown that this leads to an ability to rethink the use of a digital model in the design process and the potential for increased integration of the modelling activity within the design process.

In the next part of the chapter, the advantages of CAD applications in comparison to manual methods have been analysed. Here it can be seen how methods of manual and 2D representation fall short in their ability to carry the necessary information and are fundamentally inefficient. By explaining different levels of computer use, this document has sought to show how the design process and products have been revolutionized by the use of computers. The move starts from the transformation of CAD as purely a tool for representation towards a system which can facilitate design evaluation and other design related processes. This relies on the adoption of standards and in built tools to facilitate the creation, manipulation and storage of diverse attributes. Significantly many of the fundamental attributes to design models can be generated by software itself i.e. dimensions and similar annotations. This is one aspect of the enhancement of the design process which is also evident through the other innate abilities of software i.e. copy and paste, mirroring, rotation etc. Even the provision of guides – snapping coordinate grids etc allow for significant efficiency and economy gains.

For a long time it has been the ultimate goal for application developers to produce a modelling environment that would let the operator create a virtual version of the object complete with all physical, material and dimensional qualities. While this vision of an alternate reality is still some way off there has been progress in this direction. Operators are more proficient, machine capabilities are enhanced and the general level of associated technology is more supportive. Even the existing shortcomings of the current state of the art are not seen as fundamental obstructions and there is evidence that continued R+D will decrease reliance on physical prototypes and increase the use of computer based models. This provides an explanation of the types of model used in the design process and how they relate to the range of evaluations that provide performance data. The conclusion is that the more that the model is 'Complete' and so approaches a better approximation of reality then the greater that range of evaluations it might support and the ability to automate more evaluations [as opposed to developing other versions of the model] then the greater the benefit in efficiency and economy.

Now that the discussion has revealed that computer aided design has become ubiquitous and the development of design tools has led to the ability to construct, simulate and evaluate a representation of reality then the next challenge has been to provide tools and techniques that also provide design decision support. One possible avenue of progress is through 'Artificial Intelligence' currently a wide definition but some evidence is emerging of use in early or conceptual design stages. Equally, there are indications of the use of 'Plan Refinement' and other aspects related to 'Knowledge Based Engineering' As yet though, there is little sign of an impact from these techniques but they are indicative of the move to embody more 'intelligence' not just in the model but also in the process. This aspect is also shown in the adoption of 'Parametric Design'

Parametric design belongs to a class of operations that derive form from a set of rules and where varying the rules may produce a variety of design solutions. Instead of developing a new design model, the operator can reproduce a new solution by varying the parameter of the rule.

It has been mentioned earlier that one of the challenges for application developers and designers has been to create a cohesive model of designs which may carry real life characteristics of the proposed end products. A common use of the design model is to represent the volumetric characteristics of the object, however is has been shown that the inclusion of data describing design features will allow the testing of real life engineering features. One class of feature relates to geometry and associated functional elements. These can be defined by syntactic pattern making or rule based systems. It has also been established that feature based design is a concept that describes the ability to develop a design from components with predefined features. This can be a sequence of assembly or a sequence of operations that result in the desired form. This has attractive features but also requires that the designer has a detailed knowledge of machine operations that may be required. However there is the prospect that CAD applications with sufficient intelligence may offer the designer these capabilities.

The next section [design and manufacturing hand in hand] studied the relationship between design and manufacturing not as a set of discrete tasks but as a process. It was shown that the aim is to identify strategies which can lead to increased efficiency and economy. In fact the ultimate aim is to produce a process that makes the most appropriate and efficient use of resource. Previously the process was regarded as a series of disparate stages; however this has proved to be time consuming and inflexible. Modern thinking has identified the need to improve on this model as this would bring a number of potential benefits such as improved quality and productivity and efficiency. The pursuit of this goal has lead to new methods and management. Quality engineering applies these methods throughout all operations of a project. Computers play a central role in this systematic change. CAD and CAM are inseparable parts of a modern organisation. To this end CAPP, CAPM and CIM have evolved to support the process. The growing integration of computers which share data and support communications is the foundations of File to Factory technology. This can be seen as a logical next step given the degree of integration of computing in all aspects of design and production. Group Technology, Systems Organisation, Concurrent engineering, Design For Manufacturing and Design For Assembly are all some of the more prominent strategies being applied in modern industries to improve the whole production process. The act of process planning is the translation of design geometry, joints and features into the timeline and hierarchy of procedures, machining operations and finishing that define the artefact. There is always more than one route between design and production – the size shape and material choices all influence process planning. GENPLAN defines a systematic approach towards process planning. This system defines a method of integrating geometry, objects and components, joints and assembly into a logical production process. This information is then categorised into 'absolute knowledge' and 'constrained knowledge'.

At the end of this stage of the research it can be concluded that when the traditional manufacturing methods were predominantly classified as manual, then the quality of the product depended on the skill of the operator. Now that digital control of manufacturing is commonplace the degree of accuracy and repeatability has ensured a consistent standard of quality, similarly when process planning was essentially a human task it would inevitably contained errors and operational inefficiencies. Computer Aided Process Planning has allowed a computer to determine the optimal process and constraint checking against standards and other rules. It can also provide the link between CAD and CAM which has been identified as the key step.

Having introduced the fundamental role of computing in design, process planning and manufacturing processes it is profitable to reflect on developments in machinery and machining processes. As the technology has developed, we have seen the introduction of a wider range of supporting computer based tools i.e. automatic programming tools and cutter location data files. The technology has also been extended throughout the production line and now supports rapid prototyping and robotic controls. Numerical Control is a technique to automatically control machinery on the basis of a set of stored commands. These codes and resulting operations directly replace traditional manual methods. The technology has had the most impact on advanced manufacturing providing the ability to machine more complicated objects with operations such as the formation of compound curves. The increased complexity and capability of CNC machines has been shown to allow for more complicated operations at a greater speed and degree of accuracy. Previously data for NC machines was generated manually – with operations and tools paths being measured off drawings and manually transferred to punch tape. Now computer based applications have made this a much simpler task with automatic generations of command sequences. This has extended the capabilities of the fabrication operations and provided benefits in speed and accuracy. This has also resulted in the definition and widespread adoption of standards allowing the interchange of data between machines, companies and organisations. The introduction of 'digital part' process planning has allowed the possibility of more complicated geometries which also results in more complicated machining operations. This then results in a greater potential for conflict between tool operations which subsequently requires that the process operator must plan a hierarchical sequence of operations in order to reach the intended outcome. The development of numerical control has lead to the introduction of machines that can both manipulate the work piece and run specific operations. This functionality has now been exploited to develop a range of industrial robots that share the same lineage and can therefore demonstrate a wide range of capabilities. In areas where there is a requirement for a high degree of accuracy, repetitive tasks, hostile environments or heavy jobs then robotic operators can demonstrate significant advantages over humans. Many of the attributes discussed previously – numerical control, AI process integration, etc have enhanced the capability of robots in that their interaction and ability to respond to feedback allows them more autonomous capabilities.

The next section addressed different aspects of manufacturing planning by initially investigating discrete manufacturing and the contrast with continuous manufacturing and ultimately the effect of industries organisational changes to meet the challenges of customized, customer driven manufacturing. In essence the manufacturing process is all about an understanding of the customers' desires and the ability to convert data into objects. A manufacturing process must be organised into component fabrication followed by processes of sub assembly and final assembly. Planning this process is crucially integrated with time, cost and availability of raw materials. In a time of shortages mass production found favour as a route to market where the customer had little influence on the product. Increasingly the customer is more demanding and is exercising greater choice so a customised manufacturing process is better able to respond to a changing market. This has meant that manufacturers and customers have had to develop a tighter means of communication with integrated feedback loops. To the extent that in some instances the customer can now specify specific features of a product. In the move towards an order oriented design system the ability to fulfil the customers' wishes in a timely manner dictates success or failure. Despite good feedback loops to the customer, the manufacturer is still limited by the availability of raw material and components. This had led to the formation of extended enterprises that collaborate towards shared interests.

The pursuit of ever greater production goals has led to the concept of 'just in time' engineering. This system seeks to provide the right item of the right quality at the right place and the right time. This concept considers the totality of the project and although hard to deliver may be optimised to produce the greatest return. Basically the ruling factors in JIT systems are feedback from users, holistic production environments, flexible manufacturing processes and modularity, speed of respond to change and supply chain management. In order to satisfy market demand it is desirable to keep the diversity of products high while keeping process operations low. Technology progression is what is facilitating a move in this direction. For example a fabrication device that can perform multiple operations on different artefacts with negligible set up time.

Starting from the very beginning of CAD CAM technology and defining the offerings of the relatively new technology in order to revolutionize the traditional methods, now it can be a good time to have a look at the most recent trends in CAD CAM. The impacts of all aspects of the digital technologies on manufacturing have been compared to the industrial revolution of the previous centuries. Digital technologies are pervading all aspects of society and this impact is augmented by the ability of disparate technologies to communicate and reinforce each other e.g. autonomous vehicles. As manufacturing and fabrication became more complex there are more teams working on a greater variety of aspects of the project. This calls for closer collaboration and better communications. Consequently we can see the introduction of 'Product Data Management' [PDM] applications capable of organising all the different datasets required by the process. This impacts data exchange and management. There are also other modern means for facilitating the collaborative work of experts in different teams. The virtual environment of the Internet has provided a well established platform for initialization of the virtual teams. Through this virtual world people may gather by different means of crowdsourcing such as fund raising or finding colleagues which may not work with you in a same physical location, or even finding contractors to accomplish your projects [e.g. web sites such as Arcbazar].

Green production and sustainable products are also proven to be one of the main concerns of the societies. Growing population, limited resources and environmental issues also call for flexible, efficient and productive production lines which can reduce waste and products that use less of natural resources and produce less waste. Modern technologies can help this by accurate planning and precise testing using thorough digital models.

At the last part of the second chapter we have seen how a thorough model of products may appear in architectural and building construction projects. The term 'Building Information Modelling' or 'BIM' is referring to a relatively new system of design and documentation of design and construction data. In fact this system can connect all of the differing groupings of data and people who work within a project. This digital model applies software to conduct the flow of work and information. Similar to many other industries ambitious designers and demanding customers have made buildings and construction procedures extremely complicated over the last century. Many additional layers of data added to buildings have made designing and data access much harder than what traditionally used to be. There are also some levels of information which could not possibly be produced and accessed using older methods. A BIM model is a centralised data repository feeding all groups and being fed by all groups involved in a project. Such a model can also facilitate concurrent development of projects since different teams can update the model regularly, therefore all teams are aware of the changes immediately and can adopt a new direction or notify others of errors before it is too late. Such a model calls for a systematic change which requires every team to know and be working in a new environment. The immediate signs of improvement can be seen in facilitated documentation. Real time simulation assists the realization of design, problem solving and constant improvement of the product. Better communication and decision making during the design and construction phases are crucial benefits of such a system, the lifecycle maintenance and end of life of the project have also been planned and anticipated and could be referred to. In the end we have to remember that the ultimate productivity and efficiency traditionally come with ultimate standardization which may limit the creativity of designers, customization and uniqueness of products. Therefore there has to be a cautious consideration in the level of standardization we want to involve in every project.

3. The Industrialized architecture and CADCAM contribution

Part one: Traditional approaches towards industrialised architecture

3.1. The history of industrialised architecture

Since the features of CAD/CAM systems and the ways in which they can be used to improve the workflow in various industries have been described in previous chapters now it can be a good time to narrow the discussion down to the industry of interest in this thesis which is Architecture and building construction. Outcomes of the presence of computer aided and computer integrated technologies in the building construction industry [when regarded as a unified process of CAD and CAM also known as the 'File to Factory technology'] are commonly known as prefabricated buildings regardless of how the materials or techniques have been used to build. But what are prefabricated buildings? Are they only the cubical precast concrete buildings or factory made steel frames that existed in our cities after the mid 20th century?
The intention of this chapter is to go back in the history of 'prefab' buildings; to the time where there was no sign of computers or NC and CNC devices; in fact to discover the main reasons that had initiated this type of construction; reasons that may still convince us to see prefabrication as a versatile method of construction, to serve us in varied cases of spatial forms and site conditions or to build public buildings which people use in their regular daily lives. These reasons attracted some pioneering groups and individuals to put outstanding amount of efforts trying to harness the materials and fabrication methods in order to create spaces to fulfil the functional, aesthetic and economic requirements of their clients using various concepts, techniques and materials throughout history. Due to technological and scientific developments, once in every few years new opportunities have been opened for building producers to update their designs, fabrication methods and revolutionize their finished products consequently.

Although the main reason of this chapter is to introduce the history of construction systems which lead us to the 'File to Factory' in recent years, yet the narrative of this chapter ends right before the time when computers get involved in the construction industry since the application of digitally-driven methods are going to be discussed in the following chapters. The chapter will rely mostly on the practical use of those methods in projects. Here, there is an attempt to choose three cases of three different philosophical approaches of the File to Factory technology to be described as exemplars.

3.1.1. Introduction

The history of prefabrication in Architecture and ready-made buildings is full of stories about mankind's needs and dreams. Simon Unwin in his book [Analysing Architecture, 2009] describes architecture as a subjective system and an organization with a concept in order to give identity to the space. In prehistoric times, even before our ancestors started to form their small societies, they had always tried to shape their surroundings based on their needs. A gathering of a small group of people around a fire to pass the night time can be recognised as one of humans' first architectural design projects, and as time passed, they discovered new means to satisfy spacial needs and their designs became more complicated. They added elements to living areas to develop the quality of their lives. Shelter, walls, doors and windows were all included to deliver qualities to the space (Unwin, 2009).

Through the development of societies it can be seen that their needs also have developed. Nowadays we want buildings to be constructed with a good standard of quality even in remote locations where the building process might be influenced by severe climatic situations. Clients expect companies to produce sustainable buildings and to deliver them as planned some months or in some cases, years before. Construction companies and contractors are perusing lean construction systems and Architects are trying to fulfil perfectionism of design and may seek new forms and materials in order to realize their thoughts.

The trails of needs and dreams can be tracked from early designs right up to contemporary buildings and all the way through to the current time. They are the two important motifs which formed our world as we find it now; yet, more recently the differentiation in the fulfilment of these two elements is becoming more and more distinct. Barry Bergdoll described ‘Prefab’ as a phenomenon derived from needs which are stated as the “*long economic history of the building industry that can be traced back to antiquity*” and ‘Prefab Architecture’ expressing dreams and a “*core theme of modernist architectural discourse and experiment, born from the union of architecture and industry*” (Bergdoll & Christensen, 2008).

In the same way, as with many other influential factors and strategies [from modern materials to geometries, process and technologies], most of the prefabrication techniques have been imported to architecture from other industries. Despite the long presence of prefabrication in architecture and by all the efforts have been made to merge prefabrication into architecture, the significance we see in other industries resulted by contribution of prefabricated systems cannot be yet witnessed in architecture. Almost all of the advantages of this technology have been questioned by an ability to demonstrate quality simultaneously in design and construction as exemplified through numerous attempts during the history of prefabricated buildings. Nevertheless, it has to be said that pioneering modernist architects have had significant influences on progression in this field and have paved the way for many cutting edge methods which are being used in high-tech projects today.

The following is a brief history of prefabrication with a focus on architectural projects. It delivers a summary about the beginning of mass usage of prefab buildings in 17th century and continues by studying the milestones in growth of architecture alongside with manufacturing process up to the mid 20th century, when the world could not anticipate the huge changes which were brought to design and manufacturing by the emergence of the digital technology in building architecture.

3.1.2. The British innovations

Great Britain and their global colonization of various regions of the world served to position the nation as the leaders of prefab construction amongst western countries in the early 17th century. Having political and economic interests in numerous areas of the world such as North America, Australia and Africa also required their physical presence in those regions where they had no knowledge about local domestic materials and vernacular architecture. Subsequently, one of the interesting plans was to fabricate readymade components of the required buildings and ship them to remote areas to both provide shelter for the migrants and also to provide social services such as schools and hospitals. One of the first records of such activity dates back to 1624 in Cape Ann village [it is currently a city located in Massachusetts], where houses were built using prefabricated kits sent from England (Arieff & Burkhart, 2002).

Some other examples of colonial buildings were built later on the late 18th century and early 19th century in Australia and South Africa. These building types consisted of mostly cottages, storerooms and hospitals. The buildings were timber framed and had timber panels, roofs and walls. Although this type of construction method did not carry the same standards and qualities which we expect to be seen in modern buildings today; yet, there was a significant reduction in labour cost, time and material waste when comparing with on-site construction in the same era of history (Herbert, 1978).

The 'Manning' cottage

Looking through the history of the prefab construction industry, 'Manning' prefabricated Cottages are assumed to be the first advertised products in this field. In 1830 H. John Manning designed a cottage for his son, who was migrating to Australia, in order to provide him with a comfortable place to live in the new land. Although Manning was a carpenter and well aware of construction methods, he was not sure about the situation in which his son would be in Australia in regard to finding the necessary materials to build the house. So he decided to fabricate the building components in London where he lived. Those components could fit in a ship's hull and be transported to Australia. Each part could be carried by one person and joined together by simply bolting. John Loudon's book demonstrated the Manning's cottage which is formed by grooved posts which are fitted to panels, floor plates and triangular trusses [Figure 3 .1] (Loudon, 1839).

Manning's Cottage compared to older prefabricated buildings which were designed by the English as a step forward in details, standardization, mobility, frame, infill systems and joints. "*The Manning system foreshadowed the essential concepts of prefabrication, the concepts of dimensional coordination and standardization*" (Herbert, 1978).

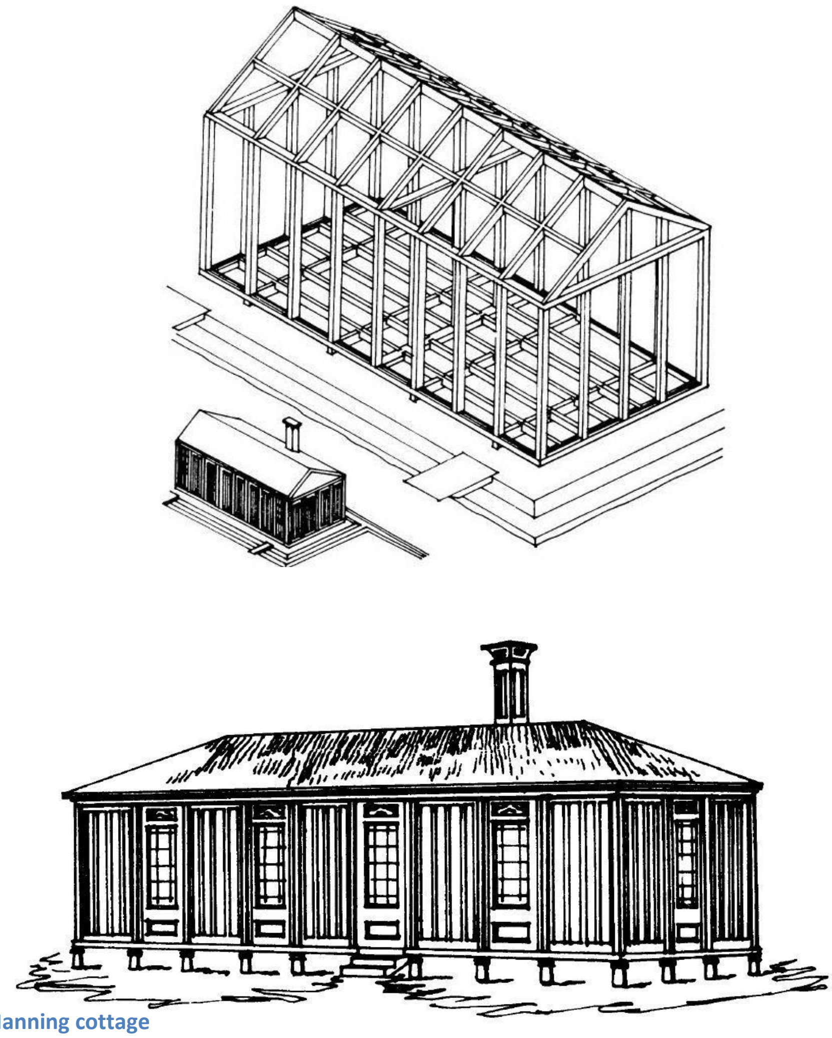


Figure 3.1 The Manning cottage

Manning prefabricated colonial cottage. Picture and description (U.S Navy Quonset Hut - Weapons of Mass Construction, 2012).

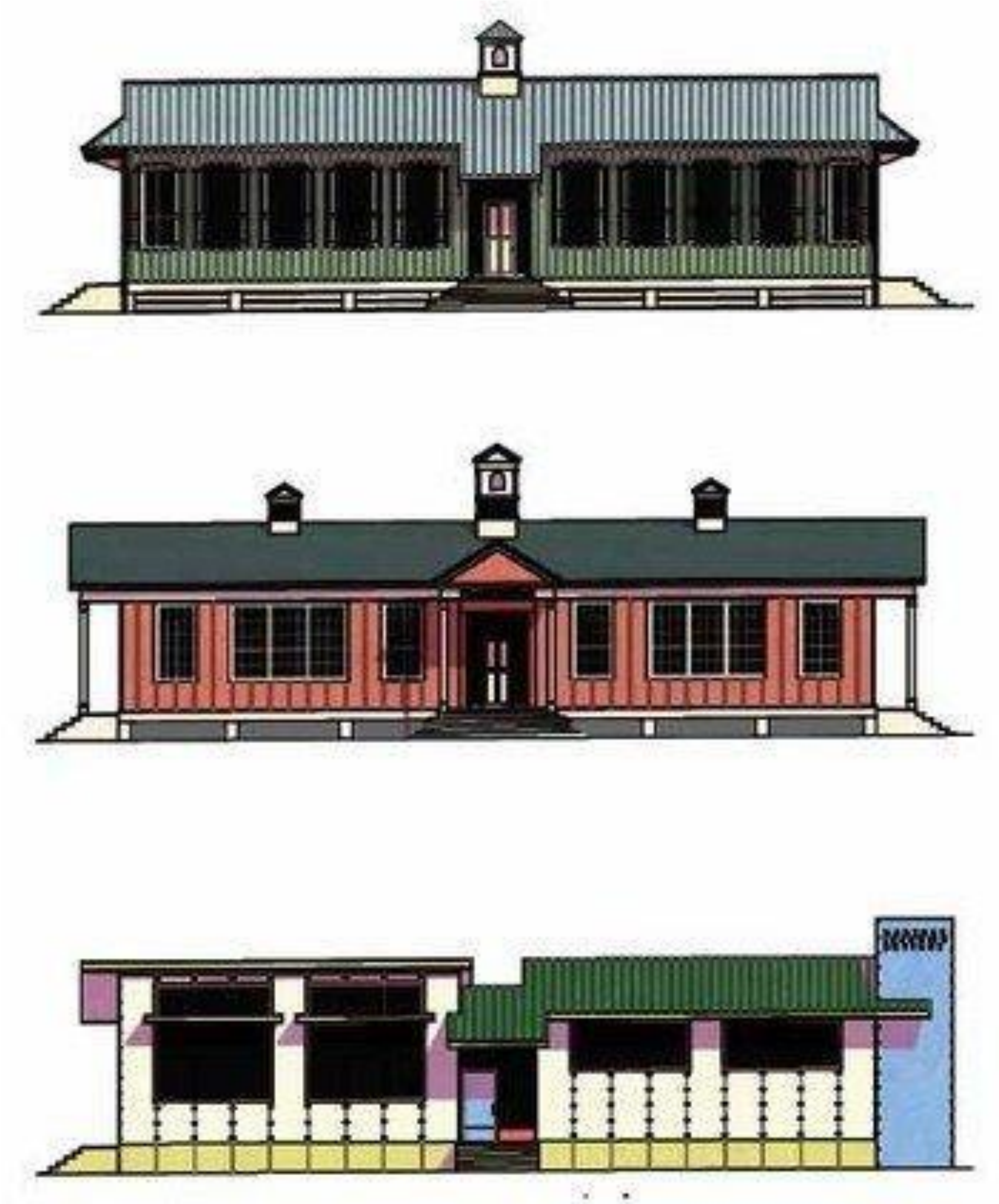


Figure 3 .2 Manning cottage types
Manning Colonial Cottages were often transformed into schools, hospitals, stores etc. picture and description (U.S Navy Quonset Hut - Weapons of Mass Construction, 2012).

Manning's Cottage was built to address the migrants' need for faster construction but also carried the characteristics of the British construction standards. A few of them still can be found in Australia [e.g. Friends Meeting House, Adelaide] [Figure 3 .3].

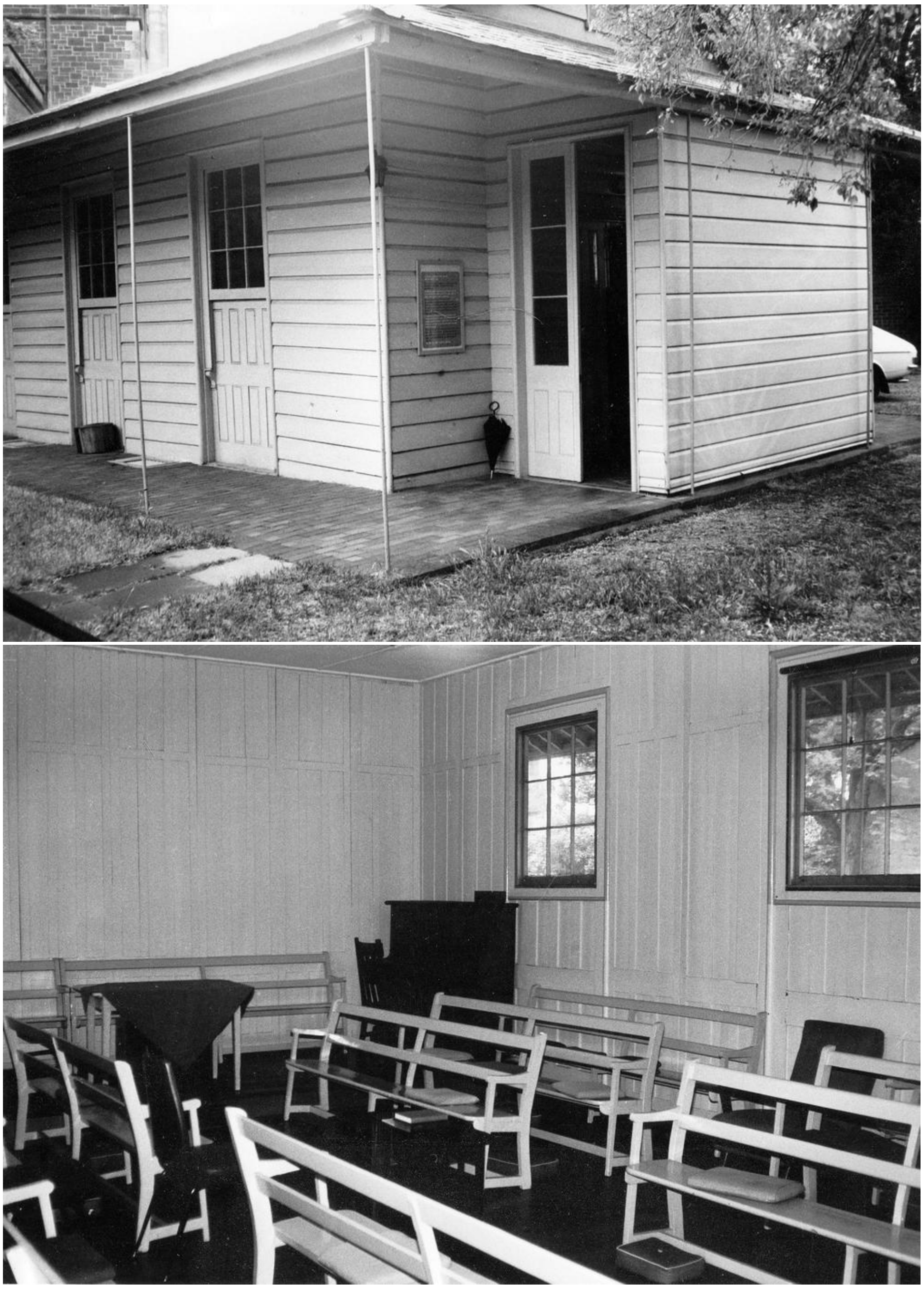


Figure 3 .3 Remaining Manning cottages Quaker [Society of Friends] Meeting House. Picture (National Trust of South Australia, 2013).

There's no recorded documentation to prove that the erection of the British prefab buildings in Northern America had significant influence on timber structured buildings this continent but some traces can be found in the 'Chicago construction' or 'Balloon Structures' [Figure 3 .4].

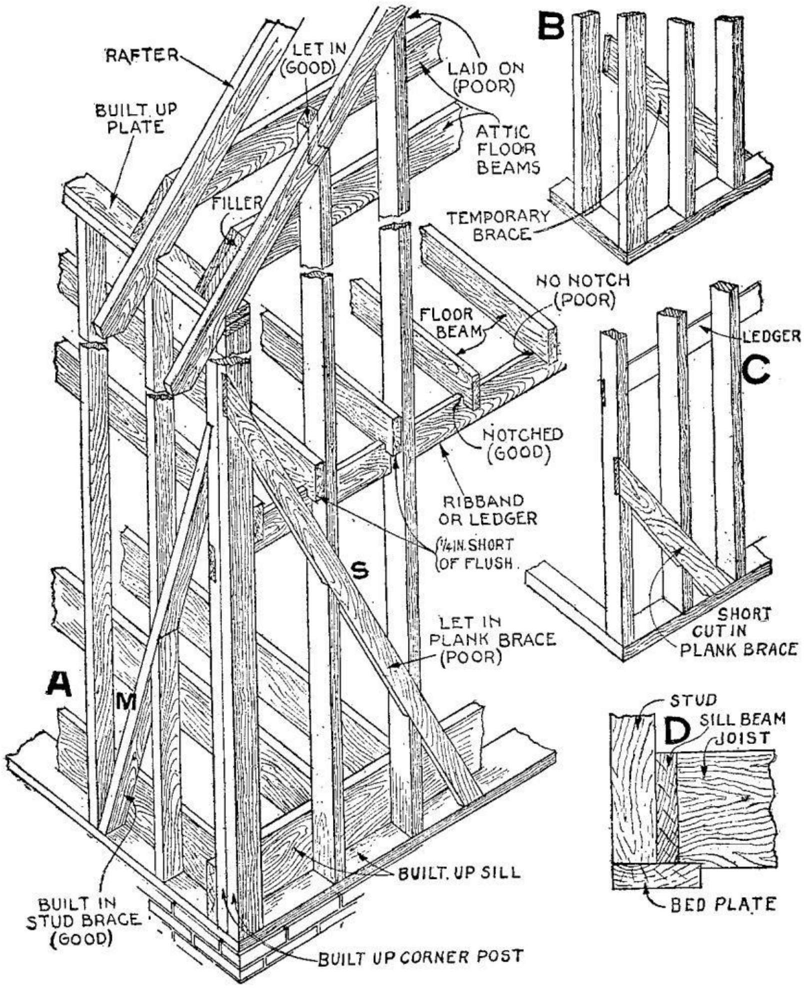


Figure 3 .4 Balloon frame

Balloon frames that assumedly were first used in Chicago. Picture (University of Seville, 2011).

Certainly it cannot be said when and by whom the first Balloon structure has been made but probably the first building in which the so called structure has been used was a warehouse built in 1832 in Chicago by 'George Washington Snow' (Miller, 1996). About a year after that 'Augustine Taylor' built the St. Mary's Church in Chicago [Figure 3 .5]. These buildings were easily erected and did not need highly trained labour in the process. Industrialized fabrication of iron nails and the ready availability of natural wood fostered the construction of such buildings. They were light weight but also had a very low resistant against fire. This caused the Chicago city which was mostly formed by Balloon-structured buildings to turn to ashes in 1871. Nevertheless due to the high speed of construction and the light weight components, Balloon structured buildings had spread in the west of America (Davies, 2005).

Iron and steel

Figure 3 .5 St. Mary's Church in Chicago
Picture (Early Chicago, 2013).

In the same way as prefab timber structure and panels, parts of buildings such as columns, doors, windows and trusses made of iron have their roots in the British Colonial prefab buildings. They were produced in workshops and then delivered to the construction site and assembled along with other components of the building. Although the prefabricated iron parts were not as wide-ranging as can be witnessed in the current theme of construction but the iron work is the forerunner of prefabricated steel which later have been applied extensively in numerous buildings in America (Herbert, 1978).

A part from buildings, iron was the material of choice used to make bridges in

England. The first bridge which was made of Cast Iron and located over the river Severn in Shropshire was constructed in 1779 and opened in 1781 [Figure 3 .6]. It was mainly made of precast iron components and assembled on-site. In a similar way to timber structured buildings, they standardized the dimensions and fixings of iron made components. Compared to timber buildings the time and cost of construction was reduced and labour with relatively less experience could erect both buildings and bridges (Smith, 2010).

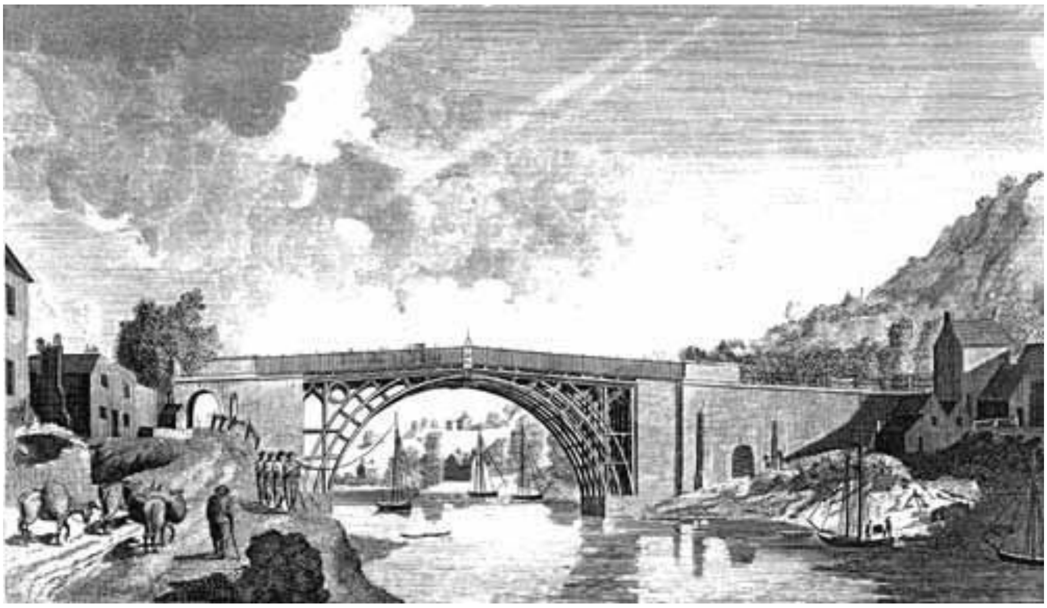


Figure 3 .6 Iron bridge
Iron Bridge over the River Severn at Iron bridge, Shropshire. Picture (Darwin Country).

At the time shipbuilders were also taking the benefits of prefab products. This gave William Fairbairn the idea of fabricating cruise ships in the mid 19th Century. At that era, the British were developing the application of iron plates in buildings such as light houses. Another important use was in textile mills. These typologies were at high risk from fire and as a solution they sought to construct them with fire resistant materials. Therefore iron frames which were affordable after the industrial revolution replaced the timber structures. One of the first examples of using iron frames in buildings is a textile mill at Ditherington in Shrewsbury, Shropshire [179697] [Figure 3 .7] (Smith, 2010).

Later on, constructors became aware of the potential of applying iron not only in

Figure 3 .7 Steel framed buildings
Ditherington Flax Mill, a Flax mill located in Ditherington, a suburb of Shrewsbury, England, is the oldest iron framed building in the world. Picture and description (Wikipedia-a, 2013).

frames, but also in enclosures and infill. Joseph Paxton's Masterpiece, the 'Crystal Palace' [1851] was an exhibition of contemporary culture and industry and was intended to exemplify Britain's position as the world's industrial leader [Figure 3 .8]. It was the first exhibition of its kind and also the first building to be fully built with modern materials [iron and glass]. All of the various parts were prefabricated and assembled on-site (Kishlansky, et al., 2008).

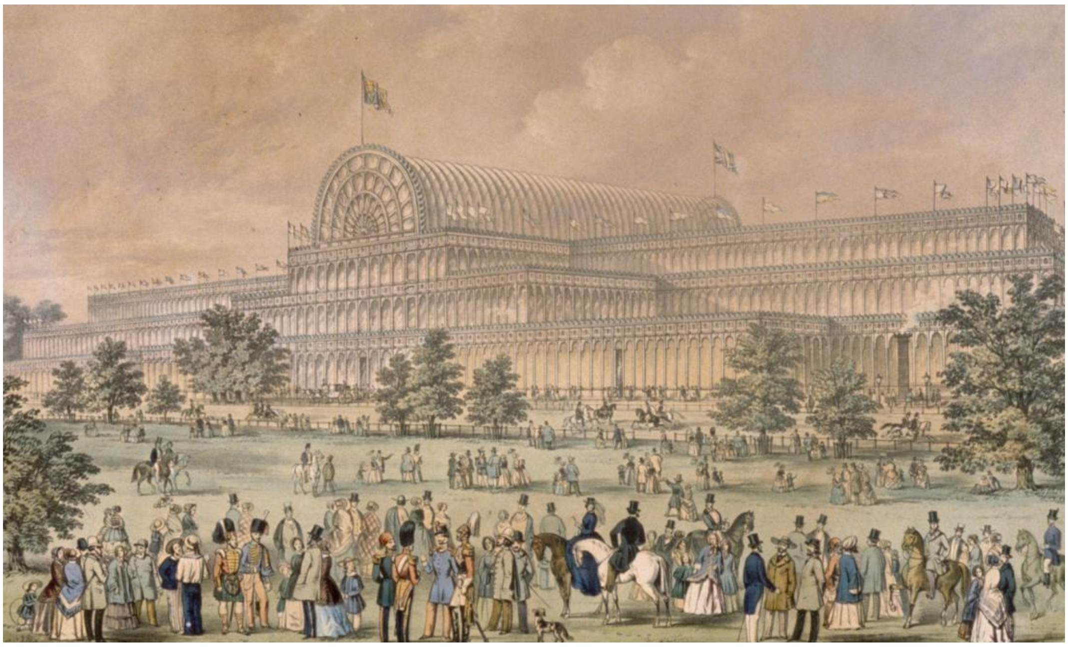


Figure 3 .8 Crystal palace
Crystal palace, an exhibition of power and technological progress. Picture (McNamara).

Corrugated metal

The Manning Cottage was the source of many developments in prefabricated frames. This effort was superseded by the innovation of corrugated iron sheets. This material replaced the previous systems of spanning, panelling and roofing using wooden panels and canvas. From the early 19th Century up to the present day corrugated iron has been intrinsic to many projects around the globe. Its light weight, and structural effectiveness made these iron sheets interesting for builders and the low price and easy installation resulted in its widespread adoption. Richard Walker was credited as among the first who noticed the potential application of corrugated sheets in mobile buildings in 1832. After 1837 fabricators started to hotdip galvanize sheets in order to protect against corrosion. Nonetheless galvanization only covered the corrosion of steel which was still happening under the coating. Rusting was inevitable especially in places with acidic rainfall and along coastal areas where saltwater speeds up the metal corrosion. Nowadays, to give corrugated steel roofs a longer life, constructors also cover the surface with a layer of paint [Figure 3 .9] (Thomson, 2005) (Mornement & Holloway, 2007).

Figure 3 .9 Corrugated steel Machine making corrugated sheets out of painted metal leaf. Picture (Trade Korea).

As well as all of the above-mentioned factors, the California 'Gold Rush' cannot be ignored as a key factor in making corrugated metal sheets popular in building construction [Figure 3 .10]. The necessity and quantity of shelters required to home the gold miners grew exponentially in the mid 19th Century. This technology was imported by Naylor from England and became one of the easiest to ship and also the fastest to erect at that time. Over 500 prefab shelters [made of Corrugated iron] which had been advertised in magazines were shipped from New York (Peterson, 1965).

Figure 3 .10 The gold rush shelters
A Shelter which has been built in the era of Gold Rush in California. Corrugated sheets have been used to cover the roof. Picture (Sierra Foothill).

Quonset huts are also lightweight prefab buildings made with corrugated iron [Figure 3 .11]. The concept has rooted in 'Nissen' hut which had been used by the British in the First World War (Brown & Lowry, 2001). These huts were named after the first site in which they have been constructed. As other typical examples of buildings which were commonly constructed with this material we can cite factories and suburban chapels.

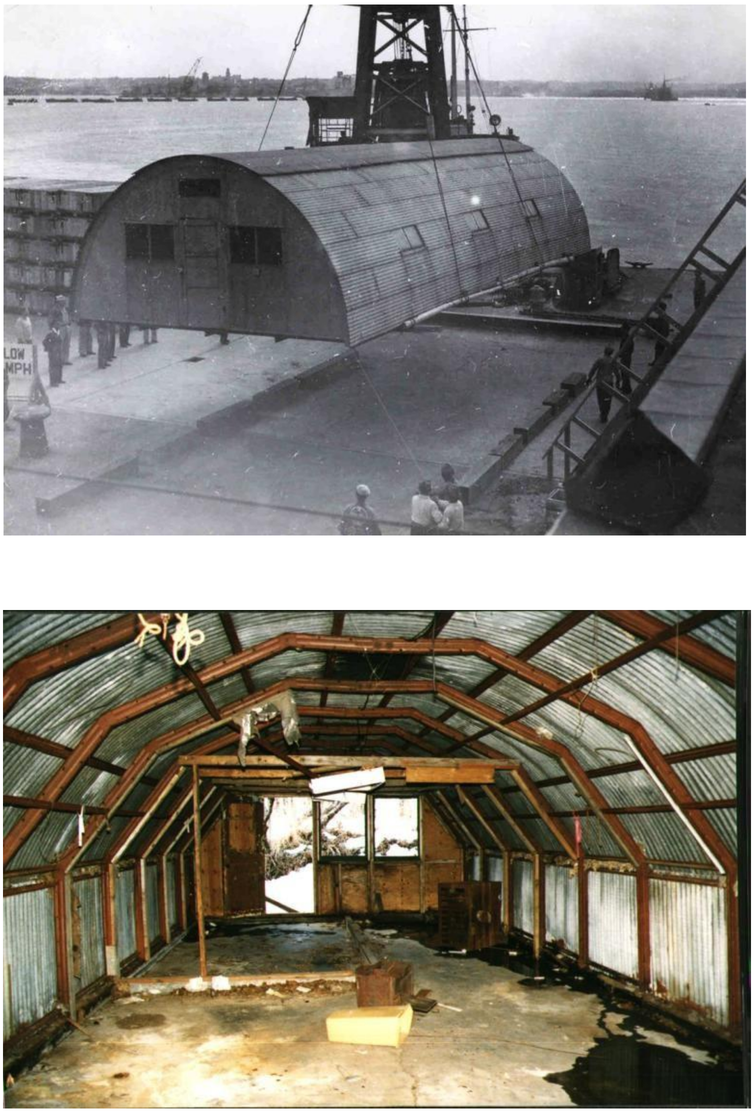


Figure 3 .11 Quonset hut

Quonset Huts were used strategically during the WWII due to the easy erection and cheap costs. Top (Wikipedia-b, 2013). Bottom (Kodiak).

3.1.3. Prefab houses in the United States

At the beginning of the 20th Century the proliferation of balloon structured buildings and the industrial boom, timber made kit homes gradually became popular. The Sovereign brothers were among the first to develop mass housing projects using 'Aladdin Homes' [Figure 3 .12].

Figure 3 .12 Aladdin homes

Left: W J Sovereign co-founder Aladdin homes. Right: Aladdin Homes advertisement in early 20th century. Picture (Modular Home Builder, 2012).

The connection of the East and West of the United States by train and mail order service which had already been used to deliver clothes or prefabricated boat parts to customers was the foundation of their concept to introduce mass production of houses which would be produced in a large number and could be erected easily and in a short period of time in order to fulfil the need for housing in the developing areas of the West. These houses were also affordable and built with standardized components. This concept also aimed for the reduction of on-site waste. While Aladdin homes established many pioneering concepts in prefabricated houses, Sears

Roebuck and Co., were responsible for developing those concepts further and through their power of planning and marketing management and promoted their business at a higher level [Figure 3 .13] (Reiff, 2000).

Figure 3 .13 Sears homes
Sears Homes advertisement. Picture (USA Home and Garden, 2013).

Their work was similar to what we see today and had a comprehensive vision from model based manufacturing to finance and further development opportunities. However all of the efforts, innovations and support did not work for both companies due to the pandemic financial crisis between the 20s and 30s in the 20th Century (Schweitzer & Davis, 1990).

In the early years of the past century construction companies in the United States tried to provide houses offering a standard quality, short construction time and affordable price. Despite all these means they did not make any significant improvement in architectural design. All the characteristics which can be witnessed from the housing projects of that period of time are the 'ornaments trying to cover the process with which the buildings had been built' (Bergdoll & Christensen, 2008).

3.1.4. Standardizing the flow of work (Fordism)

Henry Ford's car factory and the production processes epitomised in the model T automobile, offered new capabilities to the construction industry in 1910 [Figure 3 .14]. Standardization of the production process and the ability to fabricate components in an assembly line production system results in higher standard products and lower production costs and timescales. Standardization in production equates to the limitation of product varieties in a factory. This constraint lowers the fabrication waste. By producing similar components, machines need less setup time and it is also easier to fabricate and store components with the same size. Standardization and mass production go hand in hand. As a result of the above mentioned benefits of mass production, the larger the number of a similar component the less the production cost would be for unit and the higher the fabrication quality. It also applies to using the same parts to make different products. These are the basic rules of the Fordism production system. "*In the wider world it is seen as one of the key ideas of the texture of western life. The arts, music, literature, theatre, painting, sculpturing, architecture and design have all been affected*" (Batchelor, 1994).

These rules and limits have been accepted by industries, and building construction amongst them, to achieve many other capabilities which are not reachable without these constraints; but, the controversy rises from this question. What values are sacrificed and what advantages are gained through this system?

On one hand Fordism, or in other words mass fabrication, has been influential in many aspects of our lives but on the other hand it is nothing but a fabrication method which is elaborated by the development of the technology. The shape of our surrounding environment will be formed by social struggles of time and not Fordism, mass fabrication and any other production method (Sabel & Zeitlin, 1985).

The direction of technological improvements and the application of various methods in any industry have a bilateral relationship with the social context. Mass fabrication strategies are products of social cravings such as Materialism and Consumerism.

While mass production satisfied the short-term desires, it was not responsive to long term needs for stability. In this situation we are faced with perils such as abusing the poor in favour of more production, similar to what we can witness in China. It also resulted in repetitive daily tasks for the workforce and a lack of varieties in our living environment.

Figure 3 .14 Ford model T
Production of the 'Ford Model T' in an standardized manufacturing line, designed for mass production.
Picture (My Forex Trading Room).

3.1.5. The World War and prefab buildings

It was in West America where advancements in prefabricated buildings have been mainly realised. By applying Ford's mass production strategies and the progression of kit houses, most of the construction procedures switched place from site to the factories. The major financial recession that lasted for a decade in the United States deprived society from outstanding progress in almost all industries and businesses. The same theme was ruling the construction sector. Subsequently no significant movement in the form of buildings or construction methods has been recorded; but, some experimental investigations have been made in order to apply Fordism strategies in building construction.

The 'General Houses' Corporation was established by Howard T. Fisher to construct houses for rehabilitation in 1932 after the War [Figure 3 .15]. To operate in a Fordism based system of fabrication which was initiated in an automobile factory was not unfamiliar for him. His houses were different from the Aladdin and Sears houses. Not only had he used Fordism fabrication strategies and metal sandwich wall system, but he also took a further step and made houses mobile in the same way as cars. Metal sandwich panels were first used in the production of aeroplanes and using them in building construction was Fisher's most significant improvement in building construction. For the first time he used components which were produced for other industries by several suppliers in order to build his buildings. He put away the traditional values of aesthetics and the related ornaments and moved towards forms which were implied by the method of fabrication. Similar to other architects he intended to produce modern buildings exhibiting an industrial appearance [flat roofs, new materials, etc.].

Although he was not initially successful in attracting the market as much as he expected, however, paradoxically the company made a great profit through the later construction of traditional buildings (Davies, 2005).

Figure 3 .15 The Lindop residence
The Edmund F. Lindop Residence designed and built by Howard T. Fisher [General Houses]. Picture (McGrew, 2012).

The 'Motorhome' is another product whose history begins in the 1920s, but rather than being a home that is made like cars, they are cars which have been made like houses [Figure 3 .16]. These cars were first created by the Jennings Company. In 1938 they superimposed a Motorhome onto a car frame. Some restriction in the growth of this product relate to the Second World War. However we can see them in various forms and types today.

Figure 3 .16 Motorhome One of the first models of Motorhome in early 20th century. Picture (Neff, 2010).

Other American construction companies used Fisher's innovations to design and produce modern houses. The collaboration of Young [fabricator] and McLaughlin [Architect] resulted in the production of the Motorhome in 1933. The success of this product [the same as its predecessors] was below expectations. Changing the shape and using more pre-cut timber features made these 'American houses' in a category similar to Fisher's 'General Houses'. The most noticeable difference between these two was applying the modular service core in the American houses. This system was innovated and introduced by the Pierce Foundation and can also be seen as one of the first of such modular system in building construction. It provided central heating, air conditioning and plumbing systems for the house (Bruce & Sandbank, 1972).

During the period 1933-34, there was an exhibition called the 'Century of Progress' in Chicago Illinois. George Fred Keck a designer and builder built the 'house of tomorrow' and the 'Crystal House' [Figure 3 .17] to exhibit modern building construction styles from Europe and with the express interest to design and construct using modern materials such as steel and glass. Influenced by industrial fabrication methods rooted in aeroplane design, The House of Tomorrow with 12 sides and steel walls reminds the viewers of an aeroplane's hangar. The design carries the concepts of the exhibition which highlights the highest level of science and technology at that time. Whereas the house had over 750,000 visitors in the first year of the fair not even one client sought to buy a house from Keck despite the considerably short construction time [three days]. The market for the Crystal House was disappointing and Keck had to disassemble the buildings parts and sell it to pay his debts for this exhibition (Arieff & Burkhart, 2002).

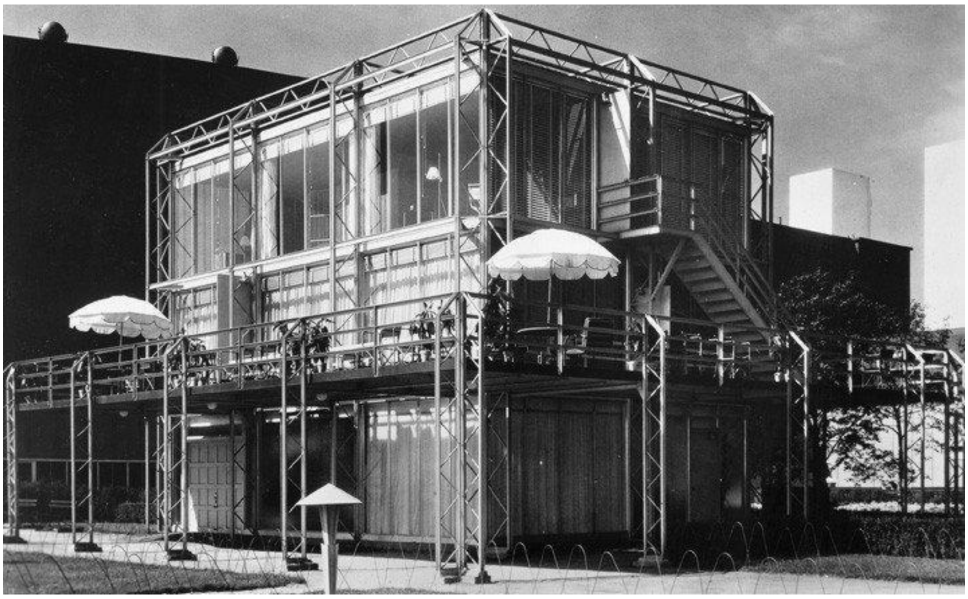


Figure 3 .17 The Crystal House

Fred Keck's Crystal House, built in 1933-1934. Picture (McKay, 2012).

3.1.6. The Post-War construction

By the end of the Second World War demand for houses rose. Consequently developments were mostly devoted to improvement of the business rather than the construction technology. By planning to build more than 800,000 prefab houses in order to accommodate returning solders, the United States government paved the way for the establishment of interest amongst architects and a focus on prefabricated housing. Some familiar names of individuals and companies such as Walter Gropius and the Lustron Corporation can be seen amongst the numerous architects, working on this sort of building.

At this time buildings had not only been built using methods extracted from the aerospace industries but also they have been built in aeroplane factories. The Lustron Corporation used these abandoned factories which were now idle after the end of the War and were producing building with enamelled sheets for interior and exterior walls. The technology was based on Fisher's metal sandwich panels. The products' features caused it to be attractive for many patrons although the company closed after the production of just 2500 houses in 1950 (Smith, 2010). This fabrication method was hard and wasteful. Thus the price of the final product was more than what most families could afford. These buildings had also been built to a low thermal standard. The steel cladding and inadequate insulation caused the buildings to be cold in winter and hot during summer. In addition the appearance was poor and not attractive.

Other strategies in the process of mass produce houses were related not to moving the production to factories but to organize and optimise the onsite construction process. William Levitt was one such entrepreneur who became known as the initiator of this system in Levittown in Pennsylvania [Figure 3 .18]. By organizing the workforce and defining a workflow to reduce waste and increase productivity, he managed to form the whole town in the period of time between 1952 and 1958. Since his group of workers could build a full house in 16 minutes. They only designed six types of houses for this town which resulted in a low variety of surroundings.

Individual houses were almost unrecognizable (Jurgens, et al., 1993). Joseph Eichler has followed Levitt's work systematically. However, having interests in art turned him against the lack of variety and poor architectural aesthetics incorporated in Levitt's houses. Eichler applied standardization in frames and mechanical services but these standards were according to architectural values and the necessary variety of products. Compared to other companies, Eichler's houses were more accepted by their users and the houses were more sustainable. This success was earned due to the high quality of the built product and a good relationship between the inner and outer spaces which is due to the architectural design quality of these buildings. The prices were comparable to the other types of houses, the aesthetic features and high level of details satisfied customers from one generation to another. Technology wise, Eichler's houses did not offer any improvements to prefabricated building construction but the notable point is the level of design and construction set paradigm which could be used in prefabricated houses (Ditto, et al., 1995).

Figure 3 .18 Levittown
Aerial view of the 'Levittown' Pennsylvania. Mass produced houses in a limited variety. Picture (American Anthropological Association, 2007).

The mainstream of the construction techniques in United Kingdom was similar to the United States. The British were using the latest prefabrication technologies [e.g. precast concrete, cement cladding, steel framing, etc.] to shelter homeless families after the World War. During this era of history, the British building and construction industry had been affected by the American developments in prefabrication and the flow of technology transfer became reversed. This flow did not conclude in just technology. The government started to import readymade houses from American companies to cover the shortfall. Differing from the products in America, the postwar housing in United Kingdom was not stylish and constructors and designers were mostly focused on time and not quality. The main cause of this shift in the direction of process and product was because these buildings were never meant to be anything other than temporary (Vale, 1995).

3.1.7. Prefabricated mobile homes

In the mid 20th century inexpensive houses with a quick construction process were in high demand. As a result 'Mobile Homes' were designed and built off site as one unit and towed to the required places [Figure 3 .19]. Similar to what was initially planned in the post war Britain, these buildings were planned to be temporary shelters and thus they even kept their wheels, though most of them remained immobile. In the late 60's 25 percent of family houses in America were 'mobile' (Manufacturing Housing Institute).

These types of houses were affordable and by the time that they were becoming popular, their designs and sizes upgraded. As 'mobiles' found their place as a permanent residence, companies began to fabricate products with larger widths starting from 8 feet and growing gradually up to 14 feet in 1969 [today each unit can size up to 18 feet in width and 90 feet in length]. Just seven years later, manufacturers moved and attached two 14-foot units onsite and created large span mobile [double-wide] buildings which were mobile only on their way from factory to the site. In June 15th 1976 a code was promoted by U.S. Department of Housing and Urban Development which rules the design and fabrication of Mobile houses and changed its name to manufactured houses as mobile homes were not mobile anymore. It is known as the HUD code (Wallis, 1997).

Mostly, architects have ignored mobile homes because of their design and construction quality shortcomings and vulnerability against climatic disasters; however these buildings comprise 4 percent of new family houses in America to themselves (Smith, 2010).

Its independent growth and wasteless construction, guaranteed the mobile homes' survival throughout almost a century of turbulent history of building architecture and construction (Davies, 2005).

The most important thing for users of prefabricated buildings is to accept them as they are. Most of them are designed and constructed in a manner which fulfils the basic standards of design and construction. Thus it is necessary to not expect more than this from them. Only recently some variations of design and construction level can be witnessed in prefabricated buildings. Among all of the products being manufactured, some only intend to satisfy the need for aesthetic features and spatial definition of various places in a building.

Figure 3 .19 Mobile houses

Mobile houses are being moved to their planned location by trucks. Picture (DHM).

3.1.8. Concrete

The First application of precast concrete can be traced back to the time when concrete sculptures were made in Roman times. Although for several centuries after the Romans, concrete remained forgotten, but in the mid 18th century 'John Smeaton' revived this material through using hydraulic lime in concrete. It was almost a hundred years later in the mid 19th century that the Portland cement was used to make concrete. This is still the most common material [in addition to water and aggregate] used to make regular concrete.

Steel reinforced concrete has its roots in wire reinforcement to make concrete flower pots. Mixing, pouring and vibration techniques accompanied by various types of cements and other additional materials, made concrete a key material and element for the success of different types of products. 'Francois Coignet' a French business man was the first to use precast concrete to make buildings. In 1896 'Hennebique' developed a gatekeeper's lodge using modular precast concrete components. Even Thomas Edison invented a single pour system to create precast houses [Figure 3 .20] (Staib, et al., 2008).

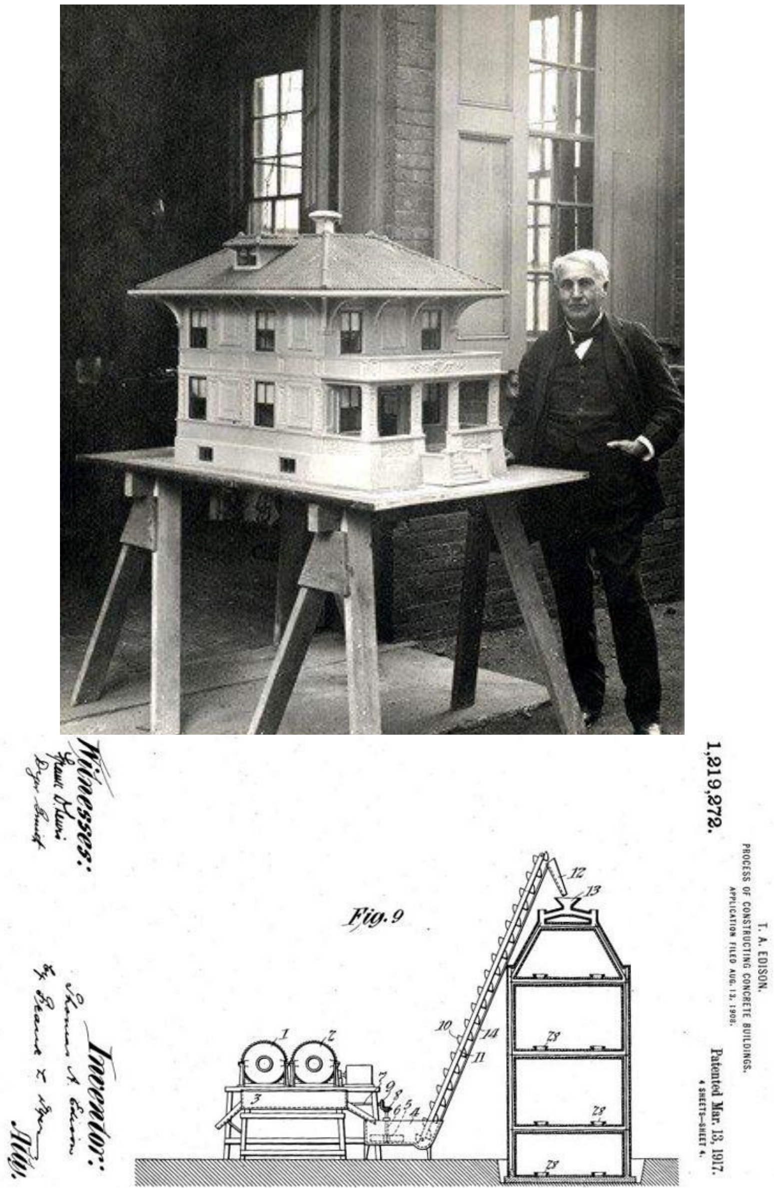


Figure 3 .20 Single pour house

Top: Thomas Edison and His 'Single Pour House Concept' in 1908. Picture (Wallpaper, 2008). Bottom: Edison's Single Pour house patented in 1917. Picture (Onion, 2013).

Prestressed concrete has more resistance against tension compared to ordinary concrete which makes it suitable for construction of buildings components with larger spans. This material owes its existence in 1886 to advancements in precast concrete systems. While buildings could benefit from the stronger material, but prestressed concrete was not applied in United States for decades and the first structure benefited from this material [Walnut Lane Memorial Bridge- Philadelphia shown in Figure 3 .21] was built in 1951. It was after the Second World War that ordinary concrete gave its place in construction to prestressed concrete due to the lack of steel.

Figure 3 .21 The Memorial bridge
Walnut Lane Memorial Bridge in Philadelphia. Picture (Wikipedia-c, 2013) .

Features of prestressed concrete made it suitable for infrastructure projects such as bridges. Though in the late 20th century this type of material drew the attention of architects and has been applied in architectural projects from then on. We can see the presence of this material in large commercial and industrial projects; however the first use of it dates back to 1971 when Luis Kahn used it to build a medical laboratory in the University of Pennsylvania [Figure 3 .22] (Smith, 2010).

Figure 3 .22 Concrete structures

The Richards Medical Research Laboratories, located on the campus of the University of Pennsylvania in Philadelphia, Pennsylvania. Picture (PLOT, 2013).

3.2. Prefab strategies

We know that the history of prefabricated buildings go back as far as hundreds of years. During this time many different types of construction materials were used in this system and many procedures have been introduced to the construction world suiting those materials to make the best use of them and to gain efficiency, productivity and the desired functions. This chapter attempts to study the various types of popular materials used in prefab construction and the different techniques that are being used to apply them in buildings. Apart from the introduction of different categories of building elements that are being used in such buildings, different materials and methods of using them to fabricate those elements are briefly explained.

The purpose of section 3.2 is to make a very general introduction to commonly used and conventional methods of prefabrication in the construction industry. It does not intend to detail all prefabrication strategies and materials; instead the focus has been to introduce the balance between on-site works, off-site works, efficiency, productivity, environmental impacts and customisation in conventional methods of prefabrication. In chapter 3.3 it can be seen that how a holistic view towards globalisation, standardisation and the neglect of local characteristics have caused serious problems in societies. Thorough the following parts of this chapter especially in chapters 3.4, 3.5, 3.6 and 3.7 we will see how digital technology and modern systems has revolutionised the balance between these factors and how it can transform and redefine the relationships in project culture and the built environment.

Without doubt studying all of the traditional and modern methods of prefabrication accompanied by an investigation of material preferences relating to each method or comparing materials based on their characteristics and distinctions in different prefabrication methods or even to query why a certain method or company has been successful or has failed require more focused research which would be out of the scope of this study.

3.2.1. Introduction

Throughout the history of prefab construction many types of off-site manufacturing techniques have been developed and used all around the world, depending on the technological improvements and acquirable local materials and the international market. In a general sense those methods have been divided into three main groups namely: componentized, panellized and modular construction. Arguably, both theoretically and practically it is almost impossible to draw a definite dividing line between the three supposedly different categories. As an example we can refer to dry plaster boards which are used to build internal walls. These panels also are known as modular dry wall system. We also should bear in mind the difference between the modular dry wall system and modular buildings where the whole module or building unit is built in the factory and moves as a whole unit to construction sites. In fact in one aspect, dividing the methods into these three bespoke categories are to depict the level of factory work needed to complete the preparation of each category before moving to the construction site similar to what which has been demonstrated in the Figure 3 .23.

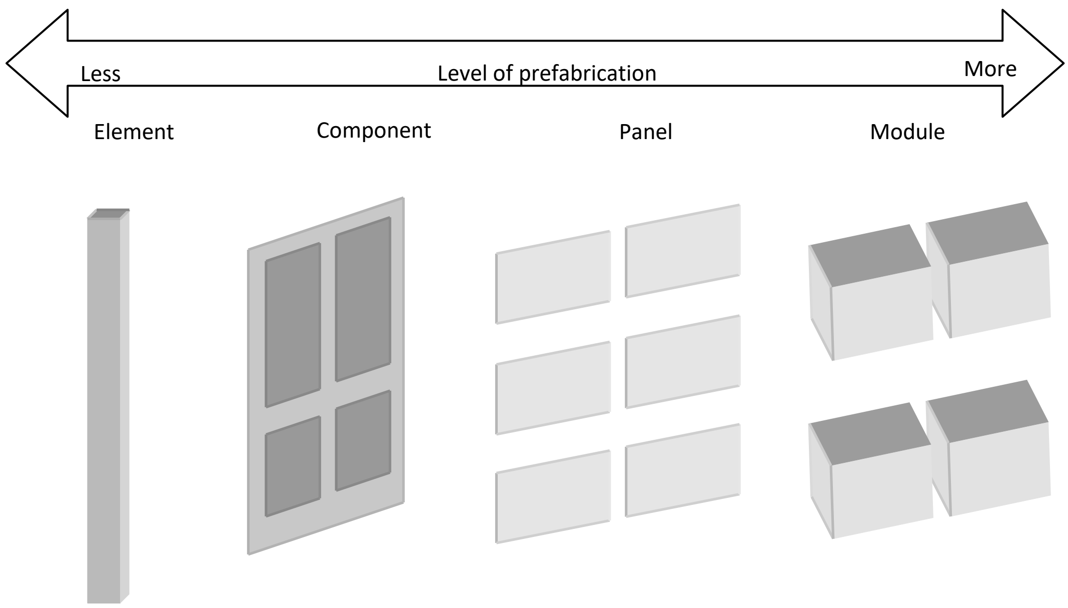


Figure 3 .23 Prefabricated materials

Dividing the construction materials based on the level of off-site operations

In the search for bringing more efficiency to the construction business and gain a higher level of productivity on the building sites, the ability to produce large panels and modules has been regarded as a milestone; especially when a great deal of work on a component has been completed in the factory and only a few operations in order to join to other parts remain to be done onsite. Nonetheless in the case of enormous buildings and huge structures there is also a large question mark, questioning the feasibility of such prefabricating process, producing large portions of them and then moving them onsite.

In most of the projects that are known as 'prefabricated' there are components designed, produced and used to fulfil many different functions while at the same time leaving few finishing operations left to be done onsite. The statistics of the real world construction prove the worth of each type [Figure 3 .23]. Panels on average are delivered to construction sites leaving 40% of site work while in modular construction only 15% of the site work is needed. In some extreme cases only 5% of the construction work is being done onsite; basically in these cases onsite construction work comprises sorting out the foundation and connections (Staib, et al., 2008).

3.2.2. Componentized manufacturing and materials

Although using discrete parts in construction is the least efficient compared to other means of prefabrication; yet, it brings the highest level of creativity, uniqueness and customization in design and construction. The smaller the components' size, the larger the quantities required. This aspect of componentized construction makes it harder for designers and manufacturers to organize numerous components. This type of prefabrication is probably the most reliant on the Building Information Modelling techniques amongst all of the other techniques due to its need for strong control and communication between different parties in any construction project to organize the design, manufacturing and delivery of components. Based on the large number of onsite operations needed to be done it is commonly compromised by human errors in joints and service malfunctions. Nowadays prefab components are usually made from timber and cellulose products, metal [mostly aluminium and steel] and/or precast concrete slabs.

Based on the nature of wood, frames can be made and erected onsite rapidly. For many centuries, builders and engineers were aware of the structural characteristics of wood and timber. That is the main reason for making it one of the most favourite construction materials throughout the history. Furthermore, scientific studies on the efficiency of joints during the past century kept the timber frames on the top of the modern heavy structure preferences in countries where using wooden structures used to be the prime choice [for example Scandinavian countries]. As demands for higher quality, quantity and accuracy of wood kits arises, more wood product manufacturers convert to the use of CNC machines. Laminated wood has been widely used in Europe both for structural and interior uses. This system which is also known as 'solid wood wall' [can be used accompanied by timber frames or individually which has been initiated by the 'Massive Holz Mauer' or 'MHM' company]. In this method the original wood which has been used as raw material for the laminated woods can have lower quality as the lamination process improves the durability of the resulted panel [Figure 3 .24] (Smith, 2010).

Figure 3.24 Solid walls

MHM's solid walls made of laminated wood. Picture (Massive Holz Mauer).

Despite the fact that CNC machines improved the capacities of the solid wood wall system, yet predominant application of timber frames remains intact due to the work of highly experienced and expert joiners in many countries such as the United States (Paevere & MacKenzie, 2007).

Wooden components and timber structures carry load bearing, elasticity and shock absorbency features in addition to being relatively cheap, easy to cut or being carved have made it highly popular in structural, internal spaces and aesthetical ornaments. Apart from all of these technical benefits, with a fair management of the natural resources it is one of the more green construction materials which are very important for companies and governments and even responsible individuals especially in the current century when green technologies and recyclable materials are highly on demand.

At the moment what is not counterbalancing the development of timber components in construction is the architecture of the buildings which are being built using this material. In his comment on this topic, 'Deplazes' notes that: "*it is therefore not the timber specialists, timber technologies, biologist or performance specialists who are being put to the test here, but instead, first and foremost, the architects*" (Deplazes, 2001).

Generally by comparing the more conventional means of construction using timber frames to the more advanced techniques such as the solid timber panels it is clear that the use of conventional framing is more popular and in most of the cases less expensive while with the latter technique comes better quality and performance, both structurally and from the energy efficiency point of view.

Metal components in building construction can be frames and/or corrugated sheets. Steel frames are very firm and relatively light. Although construction using metal frames dates back to the beginning of the 19th century when they have been used in the construction of industrial buildings and the era of the gold rush in the United

States, yet the popularity of metal material and systems in Europe happened before the Second World War.

Nowadays we see all forms of metal structures and claddings. Only a few decades ago they were only a minority of certified constructors had the privilege of building and selling metal buildings. This has led to the stabilization of those certified businesses' which brought more quality to their products. It also had a negative influence on the variety of the products in the market. In order to control the monopoly of their products they formed an association in the mid 20th century which then was followed by the formation of the Metal Building Dealers Association almost two decades later (Buettner, et al., 1990).

Standardization of metal components' dimensions and shapes as well as construction details has been highly influential on the fast growth of the metal components' popularity. Metal components such as aluminium and steel are also well suited to the file to factory process and CNC machines as they can be cut and/or formed relatively easily to shape the desired structural and covering forms. Although standardization has been the mainstream of the metal buildings, however a group of suppliers can customise the components to match the designers' intentions mostly in pioneering structures, forms and buildings which of course cause extra costs above the standard procurers' prices [Figure 3 .25]. Similar to other customized and pioneering projects, using customized metal components also need extra planning and effective organization and coordination of all groups of projects. Large spaces in metal components to optimize their weigh have made such structures desirable when there is a need for thick layers of insulation.

Almost all of the features of the 'Chicago school' have stemmed from the metal frames which have been used in the buildings which have been built at that era. Benefiting from wide span spaces providing possibilities for large openings and impressive building overhangs has made the Chicago school an everlasting part of the world's architecture [Figure 3 .26] (Smith, 2010).

The metal frames can be grouped into 5 main categories based on the features of the components being used and the final product. Single-span with girders in which there is no internal supports and can cover spans up to 70 meters wide, Tapered beams with girders which cover moderate spans, continuous beam with girders and internal supports and consequently thinner metal components, single beam with trusses and finally, lean-to which attach to other structures as support (Nageim, 2005).

Figure 3 .25 Customized steel structures

Customized steel components form the structure in Gehry's Disney Concert Hall in Los Angeles. Picture (Sergio, 2002).

As has been mentioned before metal components are also used as exterior covers of buildings. Girt systems are usually not regarded as structural elements of building rather providers of suitable bedding for covering materials which in case of the metal buildings can be corrugated sheets which has more strength compared to normal metal sheets (Smith, 2010).

Prefabricated concrete components are usually known as precast concrete. The name stems from the process which starts from factory where they cast the concrete slabs and then move them to the construction site for assembly.

Basically there are two major classes of precast concrete used in construction projects. The first one is the structural concrete which is usually covered by other materials and doesn't carry any aesthetic features. The second one is the exposed concrete also known as architectural which carries aesthetic values it also may have structural role too. Due to the visual presence, the second category has to have a better finish. Based on the colour of the additional materials concretes may come in many different shades. Apart from the colour, additives can add to the consistency of the concrete slabs.

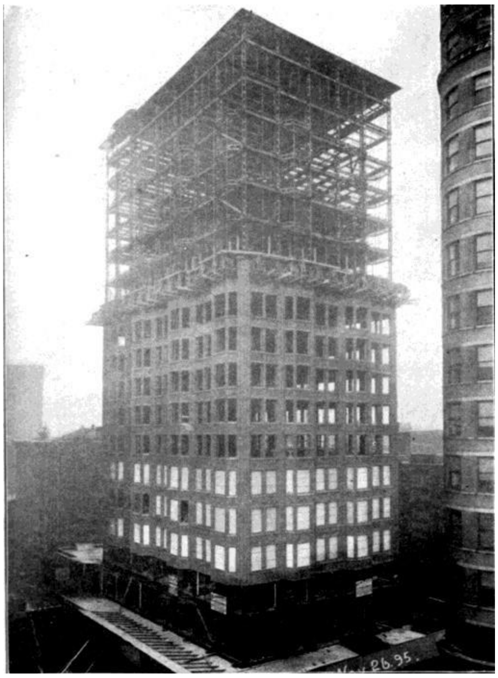


Figure 3 .26 The Chicago school
The Wind and earthquake resistant steel frame of the Fisher Building in Chicago, under construction in 1895. Picture and description(ARCHITECTUREFARM, 2010).

Casts could be made of a wide variety of materials. Steel casts are used for any purpose. They are strong and reliable and easy to use. They can be used for numerous times without causing any defects to the final product the only down point about them is the high cost of the production of cast itself. Fibreglass cast are easier to form, they are actually used to create complicated concrete forms. Their prices are considerably cheaper than steel casts but their durability is medium. Wood casts are considerably cheaper to use; they also leave a nice wood texture on the final product which usually is the most favourite feature of such casts. Compared to the steel casts they are considerably cheaper but each wooden cast may be used only a few times as they wear fast. One of the most recent trends in precast concrete production is the application of foam blocks. Doing so is a source of many benefits such as: foams used in the casting are recyclable and can be formed and reused as casts many times. The foam casts are much lighter than other kinds. As time passes they are becoming more and more popular because they can be cut and milled using CNC machines. By involving the digital technology in the cast making process, now it is possible to cast complicated forms [e.g. spiral, curved] [Figure 3 .27] and the resulted concrete components will be precisely produced benefiting from the digital accuracy. As for the architectural precast, it is now possible to add any texture to the surface of the precast slabs matching what is desired by designers. Due to the specifications of concrete parts or the casting and production process, manufacturers may use different types of cement or apply heat and cold and/or add additional supplements to gain the required strength or even colour and/or may be reducing the water consumption. In the same way as other components being used in modern construction, joints and assembly have played a key role in precast concrete construction and most of the improvements in this realm have happened through the innovation and application of new assembly techniques which made the creation of odd shaped buildings, defying the entire natural forces, feasible (Smith, 2010).

Figure 3 .27 Digitally driven concrete casting
Rotational concrete moulding by foam casts. Picture (Sambouck, 2010).

In prefab construction many of the features are the same with either the material being concrete or steel or timber. Nevertheless many of the manufacturers believe that using concrete elements is faster than metal structures as concrete elements are easier to coordinate with the concrete foundation. Clearly prefabricated concrete is faster to build as there is no need for curing onsite and also because the fabrication of elements happens in a very standard environment, the result is much closer to the advised standards. Interestingly, construction of the 'Energy Solutions Arena' [Figure 3 .28] in the United States using precast needed about a year shorter time compared to conventional onsite casting (Smith, 2010).

Figure 3 .28 Concrete casting
Energy solutions arena in Utah. Picture (Brian, 2013).

Although designers and manufacturers push all the limits to make precast concrete elements as light as possible, they are still heavy components especially compared to other two materials mentioned before [timber and steel]. Thus there are many restrictions on precast both dimensionally and in relation to mass. This makes it harder for designers, manufacturers and constructors to execute complicated precast projects which call for tight collaboration of these teams in order to gain the desirable results. Some sophisticated precast companies try to perform as much as possible of the design of the concrete elements as well as the fabrication and onsite assembly to be able to have better organizational control throughout the project. Previously it has been mentioned that using various types of moulds made it possible to cast concrete in hypothetically any shape; yet there are many other considerations apart from the geometry such as material strength, stability of every element individually and also in relation to each other, the ability of other materials to be attached to concrete or integrating the building services such as wiring and pipe work as well as insulation and even transportation. These are some of those numerous considerations which need to be made when designing precast parts. Relatively new digital technologies have made the process much easier as computer applications are capable of being deeply influential on the design of components and casts. They can also assess the products and can help with organizing the transportation and installation (Eastman, et al., 2008).

3.2.3. Planar elements

Planar construction elements which may come in a variety of shapes, sizes, colours, material and thicknesses to serve a wide range of needs in construction process from load bearing and structural purposes to insulation, sound proofing, fire proofing, dividing the interior spaces, etc. are generally known as panels.

Nowadays using light weight walls in the construction of housing projects is very popular. In the United States, amongst all of the prefab housing projects almost 2/5 of them use panellized systems. It is more interesting when we realize that in America almost 3/5 of homes are built from prefab systems (Automated Builder). Houses are conventionally made of mostly flat walls due to the fact that flat surfaces are more manageable. In fact it also can be said that features of the materials shape the building. Either way, planar materials such as wood sheets, metal sheets, plaster boards, etc. are the most popular prefab elements in residential buildings. They are easy to install, very efficient [dimensions, time, labour, heat, cost, raw material waste], very light [this is critical when dealing with load bearing properties and natural forces] and provide suitable space for insulation and building services (Smith, 2010).

Delivering panels with their structural frames is also known as 'panelization' and makes the construction process much faster than dealing with making frames with the basic components on the construction site. With the tight economy of the recent decade, and customers being under pressure regarding loan repayments, sometime in small and especially in residential projects it makes a substantial difference if the construction completes even only a few weeks faster than with conventional systems even though factory based manufacturing may cause a slight extra charge to the overall construction costs. Apart from the financial benefits, such a decision brings a considerably higher level of standard to the project both technically and aesthetically as well as avoiding the possible influences of harsh weather changes on site.

'Structural Insulated Panels' or 'SIP' [Figure 3 .29] are framed panels consist of several layers of possibly different materials each carrying features [such as fire resistance, thermal insulation, sound proofing, etc.] grouped together to generally infill the space between steel and concrete frame structures in residential and small commercial projects. Based on the layers of material used in panels they can be used both as inner walls and outer walls.

Being used from the early decades of the 20th century, it took almost a century of improvement for the SIPs to become a commonly used material in the construction business; yet in traditional markets it is still facing challenges to compete with the cheap workforce using older methods. Amongst all of the reasons of the SIPs improvement it was the CNC technology which made the big difference in the use of this concept. Rapid pace in production, extreme precision, minimized waste, digital planning and straight forward assembly and erection onsite are amongst the valuable benefits of CNC technology. Based on the design and demands of builders, fabricators can insert internal cavities within the panels to allow the wiring or other type of building services. Since Structural Insulated Panels only have 3% of thermal waste compared to the normal frame walls which waste 25% of thermal energy on average, they appeared an to be ideal option to build large fridges. On the other hand SIPs are very sensitive materials which can be affected by severe climatic situation while in storage. Many conditions are applied while storing them such as keeping them dry and distant above the ground (Simpson & Smith, 2007).

Figure 3 .29 Structural Insulated Panels

SIPs come in a large variety of thicknesses and materials and are used for different purposes. Pictures (Normanton, 2007).

Curtain walling as a system of construction is used to cover the exterior walls of buildings, mostly tall commercial ones. The main application of such a wall is not structural [only to bear their own weigh or resist against wind force] but only to keep the building occupiers out of the harsh weather of outside. Walls which are not considered as structural can be built with a wider range of materials compared to load bearing walls. In the case of a Curtain Wall glass is normally used.

There are several methods to apply them on the building facades [Figure 3 .30]. Bond systems which use aluminium mesh attached to the structural frames to provide bedding for covering materials.

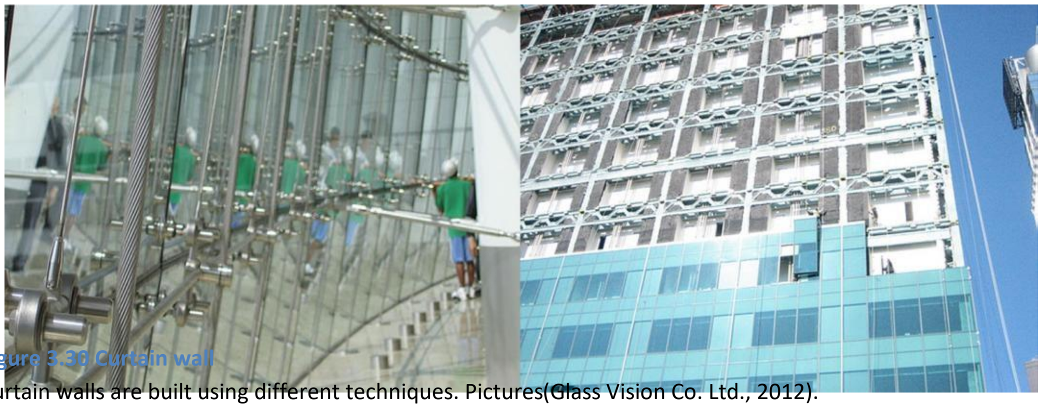


Figure 3.30 Curtain wall
Curtain walls are built using different techniques. Pictures(Glass Vision Co. Ltd., 2012).
Left: Spider spot connections
Right: Bond system

There is also the 'pack system' which can be a combination of glass and aluminium being prefabricated and brought onsite then assembled and attached directly to the building structure.

Spider connections which provide spot connection of glass on the facade. In such system there can be more than one layer of materials used to provide better insulation. Among all those mentioned above the pack system or the 'Unit system' is the most desirable choice since most of the work can be done off-site and high level of precision and easy installation increases the whole construction speed. In opposition, the down point in the application of this system is the risk of creating plain building exteriors. In addition joining two units can be very critical as they need to be waterproof and also have plenty of space between them to allow expansion due to thermal changes (Knaak, et al., 2007).

Similar to the curtain walls system cladding panels are also non-structural components of a building; therefore these two systems share many similar features, serve almost the same purposes and must embrace many technical production details in order to make them applicable to the exteriors, such as facing climatic changes and being water and air tight to prevent damage to the building, help the energy efficiency and the welfare of the people using it. Cladding panels may be used as individual layers or accompanied by layers of other materials, each designed to serve one or more purposes.

Climatic forces such as wind, gravity, the difference of the air pressure between the outside and inside of buildings, etc. can cause the water travelling from the outer skin of buildings toward the internal spaces. Additional technical details have been used to neutralize such effects. As an example in cladding systems chambers have been used to attenuate the pressure difference. One of the forerunners of the development of the cladding panels is William Zahner whose work has provided extensive construction details to make the cladded walls feasible and more convenient amongst commonly used construction techniques (Zehner, 2005).

Generally this sort of panel system when used as prefab products are manufactured off-site and attached to the bedding provided for it, either being the aluminium mesh attached to the structural frame of buildings or the structural frame itself. Various types of building cladding are not all prefab panels as for example stone cladding can be placed in the frame provided to act as the climatic barrier. Stone panels also may simply have anchors of different kinds attached to them to let them connect to other building components.

As has been mentioned before, cladding panels are not structural components of buildings; therefore a wide range of materials and a large variety of thicknesses can be used to make such walls. Nonetheless, amongst all of the materials used in such panels serving as the outer layer, metal sheets are the most popular. These sheets can come in numerous colours and since their weight have been optimized for the area they cover, particularly in the case of aluminium composite sheets, these are mostly used in large buildings where the structural weight of skin materials is a critical feature; yet, due to the intended visual features of the final product as can be seen in the Figure 3 .31 many other materials like titanium, copper, etc. may be used. Several processes may be applied to metal sheets to prepare them for facade use [e.g. to add support against ultra violet rays for colour stability and/or rust]. Since metal cladding panels are very sensitive to damage caused during transportation, thus after pressing and forming the sheets manufacturers normally avoid to assemble parts on secondary frames and deliver the panels to the site where they are going to be installed on building frames. Another drawback of using metal sheets on their own is that they can't stop the thermal exchange between outside and inside of the building so they need a greater degree of insulation. Similar to other facade panels metal cladding also need space allowing for expansion and also effective water proofing systems especially on cold days when contraction may widen the space between sheets which in that case insufficient consideration my cause leaks which are dangerous for the building. Panels such as aluminium composite have a layer of foam in the centre to prevent sheets from distorting and forming surface defects.

Figure 3 .31 Metal cladding
Marques De Riscal Hotel, Spain. Different types of cladding sheets have been used to serve the designer's intention. Picture (Flicker, 2008).

Another material used in panels covering the facade of buildings is wood. Because water permeates through wood it is often necessary [especially in larger buildings] to cover any sort of frame or sub-frame with waterproof material and attach the wood panels onto them. In the case of using them in small buildings sometimes it is possible to attach the wood cladding directly to frames. The permeability of wood can also work positively as wood panels can let the moisture gathered between the layers of building skin dry at the outer surface of wooden panels. This kind of cladding also offers better thermal performance since wood does not conduct a large amount of heat. It is also important to remember that wood components are formed from a natural construction material which means they are recyclable as well as hard to maintain. They are sensitive to extreme heat, dryness, moisture, pests and funguses.

To make them more resistant there are several methods of treatment using natural and chemical substances.

Stone, ceramic and similar materials are also used on the buildings' facades. These materials can be used in order to create complicated forms but they should be cut accurately by the computer numerical control machines. Since transport causes a small percentage of defects on components, they can be installed on sub-frames in factories which mean high level of standards and controlled process, efficiency and less site work which can be critical in severe climatic conditions. Bearing in mind that this type of materials are among the heaviest which may cause the prefab production using them to be less useful; nevertheless new technologies are used to reduce the thickness of these materials in order to make their transportation easier and the exterior walls lighter (Ward-Harvey, 2009).

Any building component from the block shaped materials family can also be used as cladding to cover external walls. Such walls could be constructed both onsite and in the factory. Onsite operations are very slow and only financially advantageous in areas where the workforce is cheap. In factories bricks and block work can be arranged as prefabricated panels and transported to the site and installed. Similar to stone and precast blocks, brick is a heavy weight material which makes prefabricated panels not ideal for transportation. In addition bricks are easily broken which calls for extra care and attention when moved and installed as sensitive inflexible panels. Since bricks are small modules repeated throughout the surface of buildings, it is important to design a concept for the bricks' configuration to divide the length of buildings into the lengths and/or widths of the bricks used and also create patterns to maximize the strength of the panels and also add aesthetic values to the buildings' facade (Duggal, 2009).

So far the discussion was mostly tended toward the external use of panelization while, panels are also used to form the interior spaces of buildings. Fast construction and cheaper costs compared the traditional materials have made them the most popular material in the transitory construction. Using these materials has enabled the property owners to change the interior spaces of their buildings based on the need of the tenants. They are made from numerous raw materials and come in various thicknesses and with various features. Internal panels are usually installed on frames of wood, aluminium, etc. and the cavities between the two surfaces allow space for building services, insulation and so on [there can be materials which block the heat waste or as it is necessary in hospitals block the x-ray radiation, etc.].

3.2.4. Modular construction

This trend in construction is a result of the post war crisis when all types of buildings were in demand in the shortest possible timescales. Such requirements had led to construction of portable and short-term buildings in the mid 20th century. In order to cope with the new requirements engineers have needed to develop new technologies, construction techniques and materials to realize such concepts. Although most people still identify modular buildings as the products of that era, nowadays modular buildings have become a regular approach to efficient mass production, featuring the highest level of standards and execution quality especially in developed countries. As has been mentioned in the introduction section some extremely accurately planned buildings use the most prefabrication procedures as that can leave only 5% of the construction work to be performed onsite. Prefabrication and modular building is now becoming an important aspect of the available construction techniques due to the versatility and capability of these approaches, but in public culture they are usually regarded as the same technique. Anderson quotes in his book: "*it is unfortunate that the terms 'modular' and 'prefabricated' have become interchangeable in many people's vocabularies as it greatly confuses the viability and applicability of different available prefabrication systems*" (Anderson & Anderson, 2006).

As the modules become larger it means site work is going to be easier; yet, large modules constrain the variety of shapes in a building. The smaller the modules are, the bigger the variety of forms that can exist in one building. Basically the larger the modules are, the higher the level of standardization is going to be.

Precast modular units which were the mainstream technique in prefabricated buildings in the mid 20th century are not that popular anymore except in nonresidential buildings in suburbs [Although some recent efforts have tried to stylize the new modular concrete buildings in cities similar to what is shown in Figure 3 .32]. Apart from the aesthetic damage that they have caused to cities due to their basic design and lack of creativity, they are also very heavy, therefore hard to transfer from factories to construction sites. Each precast unit can weigh up to 50T on average. Such volumes of mass, call for heavy and expensive machinery both in factories and more importantly on site to handle them (Smith, 2010).

Figure 3.32 Modular concrete structure

NYC's first Prefab Steel and Concrete residential development. Picture and description (Rackard, 2013).

In order to make the modular units more affordable for residential projects it was vital for construction companies to make changes and direct their attention toward lighter materials and more cost effective methods [timber, steel and aluminium frames]. Timber frames are the most popular in smaller projects with less than three units standing over each other. More than this number of units requires stronger frames in the lower units which in the case of timber frames, costs grow exponentially therefore becomes not a cost efficient solution. Modules are made in different fashions. Based on the dimensions of modular units then all of the unit components [floor, ceiling and walls] can be made in the factory and assembled there and moved to the construction site or if the modules' sizes and/or shapes make it impossible to be transferred from factory to site, they may produce the whole unit in the factory and then dismember parts, flat pack it and move it to site and reassemble the parts [Figure 3 .33] (Staib, et al., 2008).

Figure 3 .33 Modular timber structure The whole unit can be built in the factory and then moved to the construction site. Picture (R. G. Stones, 2013).

The most evident problem of using modular units in construction is the lack of variety in the shape and dimensions of the resulting buildings [Figure 3 .34]. In fact the shape and size of rooms are limited to the dimensions of common modules and the number of units which can be attached to one another. The dimensions of rooms and any components or elements used to fabricate them are dependent on the delivery standards. To meet these regulations some sizes may need to be reduced and some may become larger to, for example, survive the stress occurring during transportation. Apart from the width and length of the rooms, the ceiling height is also limited to the space constraints of the factory and the roads' regulations and limits for the size of laden vehicles and Lorries. Modular construction needs a very precise sequential organization of off-site and onsite activities as well as site delivery. In addition, as it has been mentioned before in order to make the best out of this method and benefit from the advantages of modular construction advantages, the general trend in planning should be to execute as much as possible of the work in the factory rather than moving it to the construction sites (Smith, 2010).

Figure 3 .34 Mass produced modules
Mass production of modular units can cause lack of variety in products. Picture (Shaw, 2013).

Metal frames used in modular units make them suitable for large buildings which are usually classed as commercial. These frames are stronger and stiffer than timber frames; therefore they do not need so many changes to make them suitable for transportation and delivery. Such features have also made them popular in countries where ground conditions and earthquake risk are an issue [mostly among the south eastern Asian countries]. Strong structure also means that much of the work can be completed in factories and the unit will be delivered intact. The internal cavities also provide enough space for building services and insulation. The modular method has to be seen as an efficient way of construction, and when accompanied by a well organized system of management, has become a fast developing method of prefabrications throughout the recent years. One of the main drivers, apart from the efficiency and fast execution, can be the poor economy of recent years. Due to financial problems governments are less able to maintain the economy of their countries. Interestingly, based on the MBI statistics [Modular Building Institute] at the peak of the financial crisis of recent years where many large scale construction projects have come to a halt, the largest growth of the modular projects has happened in public buildings which have been ordered by the government of the United States of America (Smith, 2010).

3.2.5. Modern Methods of Construction [MMC]

Nowadays the question of using natural resources is highly sensitive in both quantitative and qualitative regards. Generally speaking it is of a high importance to consider how much of natural resources are going to be used and how much waste is produced in order to construct any building as well as in regard to what it might consume throughout its lifecycle. Based on this concern the Modern Methods of Construction [MMC] has been initiated by many of construction companies who use timber elements in their buildings. MMC has been developed to cover a large variety of timber construction methods. The type of timber used in this system is mainly similar to what is used in traditional methods of fabrication and can be used to produce offsite manufactured modules for complete buildings, panels, panelised modules and components as well. MMC has developed innovative on-site methods and suitable materials to improve older conventional systems of construction (Hairstans, 2010). Nonetheless the controlled environment of factories usually provide better quality and waste control. A range of research has been funded by Waste and Resources Action Programme [WRAP] to show the level of waste reduction in MMC systems compared to traditional methods. As an example, reports show that MMC has reduced 22% of waste in light steel frame construction and 11% for timber frames compared to conventional systems (BeAware, 2009).

In a MMC system, waste production has been divided into Manufacturing waste, Distribution or Installation waste, and End of Life waste. In the manufacturing waste management strategies MMC suggests that standardisation of end services and artefacts as well as the raw material can help to eliminate waste to some extent. For this purpose service providers must encourage their clients to choose products which have more recycled and recyclable materials in them and choose products which can result in less waste in their production. On the other hand customised designs and unique products that are expected to be delivered in a limited timeline can limit the manufactures' ability in regard to waste management during the manufacturing process. Sometimes up to 50% of the weight of the waste produced is allocated to packaging. Therefore distribution methods could also have a significant effect on environmental impacts of every product. In the installation category MMC has developed many strategies to reduce waste. These strategies require staff to be educated and trained in order to make them fully aware of the consequences of waste management. There are also considerations for the product's end of life. MMC systems suggest that products must be designed and produced in such a way that all components could be disassembled and recycled or possibly reused. The problem here is that some customers may not prefer to use recycled components or updated building regulations can mitigate against such action. In the case of some materials it could be difficult or even impossible to separate them from each other in order to recycle (BeAware, 2009).

In a similar fashion to many other modern techniques, modern methods of construction also try to develop methods directed towards producing better products in better, more innovative and more efficient ways. The objectives of such a system consist of higher productivity, greater level of quality, more customer satisfaction, less adverse effects on the surrounding environment and better control over the timescale of the project (Barker, 2006).

In a MMC system the lean approach towards production plays a key role throughout the process where all groups and individuals have to be committed to reduce non value adding activities, towards decreasing process time, increasing standardisation and reduced variability, simplification of the process and products, enhanced flexibility and also raising the transparency of the whole process, products or services (Hairstans, 2010a).

Although MMC considers the use of many conventional building materials sustainable production considerations has made timber as the preferred material due to its unique characteristics. Apart from the fact that timber production needed much less energy compared to steel and concrete, it is also much easier to recycle and less harmful for the environment. Albeit using timber needs a sustainable resource and environmental management in order to control the environmental impacts of using trees for construction (Dickson, 2002).

In order to take the full benefits of MMC system in construction projects it is critical to consider necessary factors during the design phase. Factors such as durability, standardisation, design life, movement, robustness and also fire resistance could be some of the highly valued elements of design in this system (Hairstans, 2010a).

3.3. Industrialised architecture; cure or disease?

3.3.1. Introduction

The intent of this chapter is to investigate the impacts of globalization of the construction industry on local communities. This requires a study of modern building forms and construction methods as well as global standardization imposing the same values on varied societies in different places of the world. Consequently in the end it summarises the fact that customization in the adaptation of modern architecture based on local characteristics and personal preferences are both vital and inevitable. We are already aware of the need for prefabricated construction frameworks which provide faster production process accompanied by less waste during the construction and product lifecycle. It has also been mentioned that these products have to be made in large numbers to be responsive to fast growing demands. Green production policies and market competition have caused a rapid growth in the quality, efficiency and productivity of artefacts and production systems; yet, one very important feature in the production business is customization. Today it is important for many products and services to match the needs of the users. In the building design and city planning domain these features are even more critical since buildings and urban spaces are in direct contact with peoples' daily lives and have long term presence and impact on societies and environment. But what are the local elements that have been influential in local architecture for thousands of years and how they have been changing during this time?

As an example, the following section's focus is on studying the local architecture of different parts of Iran which have diverse local characteristics in the past and in the modernized world. Basically the task is to investigate the differences between the climatic and cultural characteristics of the regions, how different the historical architecture in different areas used to be and what is the quality in the current situation? To do so, the study first tries to present a theoretical overview regarding the historical concept of urban settlement and the architectural features of vernacular houses and contemporary dwellings. The research develops on the basis of comparative analysis conducted on the socio-cultural and environmental performance of traditional and contemporary building types which have been built in Iran. These differences used to appear in totally varied types of architecture depending on the local characteristics.

As it has been mentioned before, the intent of presenting this section is to illustrate the possibility of adverse impacts of globalisation, the industrialisation of architecture, a high level of form and material standardisation over the local architectural culture without suitable considerations in regard to the local characteristics and individual needs. Section 3.3 demonstrates the neglected values of both traditional and modern architecture in the prevalent construction culture which has formed our living spaces, societies and ultimately our culture. Although local culture, environment and architecture of the past and present of two different regions of Iran have been discussed in this document, yet, the domain of this phenomenon is not limited to these two regions or just this country and similar effects have been experienced in most places around the world and also in many different countries such as the United States [e.g. repetitive houses in Levittown], Britain [e.g. high rise residential towers in Glasgow], India [e.g. Chandigarh], etc. . The choice of location for this research is solely related to the author's background, personal experiences and studies prior to this research. In fact this section creates a basis for a discussion to show the consequences of the conventional methods of modernised construction industry on societies and environment or to demonstrate the fact that high level of standardisation has been chosen over vernacular and customised construction because of its momentary financial benefits whereas it is known that the adverse impacts over local culture and environment caused by extreme standardisation will result in many troubles and costs in the future to solve these problems; similar to what which has been already experienced in many different locations.

Going through the events of past century it can be noticed that after the Second

World War, the process of modern architecture [modern architecture has varied description and scope and is primarily based upon the industrial revolution of mid eighteen century. The term is widely used to describe the architectural movement at the beginning of the 20th century] was subject to a major transformation that not only resulted in changes to modern architecture in western countries but also had a great influence on the architecture of other countries. The extent of war destructions and the socio-economic necessities of reconstruction and revival tasks brought modern architecture and urbanism into consideration more than at any other time in history. 'More', 'Cheaper' and 'Faster' were three fundamental trends that the European post war societies were seeking to follow in the reconstruction and revival of their war-torn cities. Accordingly, standardization appeared to be the main solution in the process of construction and renovation of the buildings and cities. Hence, due to the time and cost shortage, the application of previous forms, structures and construction techniques were abandoned, and architectural decorations and details were excluded in order to achieve a higher level of productivity and efficiency in building construction. This approach to the creation of new buildings and the revival of cities has become even more intensified after the Second World War (Mohammadzade, 2009).

High impacts of the post war shortages in Europe had generated a style of buildings and urban construction which has been replacing the local architecture in developing countries (where they were technologically dependent to Europe and United States) ever since. Nevertheless the penetration of this relatively new style has mostly happened while lacking any sort of domestication to match the local social, economic, cultural, climatic and rational grounds and identities. Although there might be some adaptation in methods, structures, forms and spaces, yet the majority of them are now regarded as shallow and not fully compatible and practical in peoples' daily lives. Consequently, what is formed as modern architecture in developing countries appears to be deprived of any local identity, products that affect their users in every possible way but are not responsive to their needs in regard to the climatic, cultural and social considerations. Therefore, the incompatibility of architecture with the local necessities has resulted in the increasing use of energy and natural resources, causing modern buildings and cities to become increasingly unsustainable both socially and environmentally (Mohammadzade, 2009).

3.3.2. Iran on the way of modernization

Being one of the pioneering countries in the realm of engineering, urban development, architecture, form generation and building details during the past centuries has made Iran an attractive location for inspirational research in the history of design and planning. Nowadays the rich architectural background and the remains of the historical buildings and cities are still the main source of tourist attraction in different parts of Iran and are regarded as the national and cultural treasures of the country [Figure 3 .35].

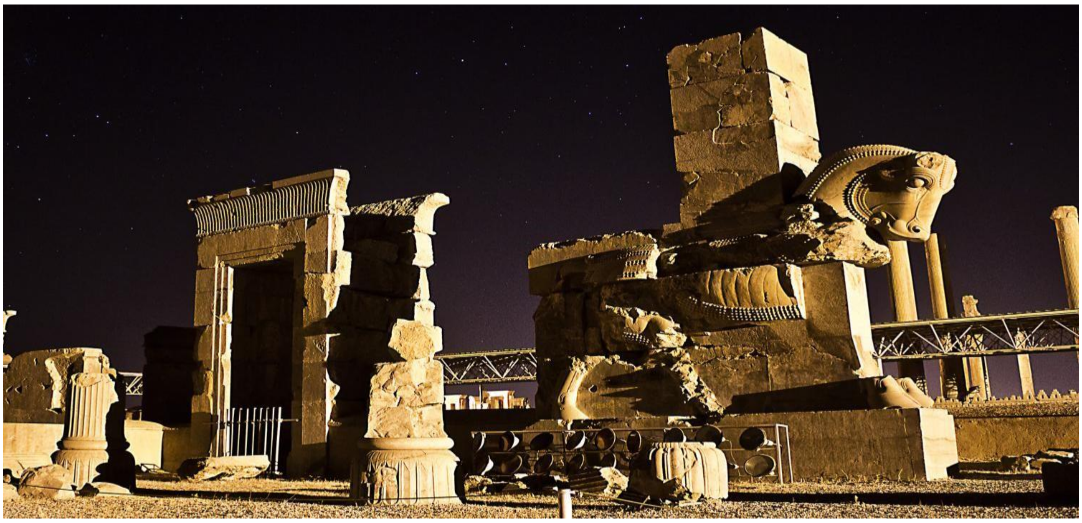


Figure 3 .35 Persepolis

'Persepolis' locally known as ' Takht-e-Jamshid' is an ancient city in central Iran, considered as a modern city for its time. Its structural, construction details, infrastructure and artistic features have made it a unique piece to exhibit the engineering and architectural proficiency existed at 515 BC. Picture (wikipg, 2013).

Being dragged into the Second World War by the invasion of the Russians from the north and the British from the south, Iranian cultural and technological grounds have been severely influenced by its aftermath. After the war, while the source of governmental power was being manipulated by the western countries and more distinctly by Britain and the United States, the country was gradually becoming fully dependent to them technologically. From an architectural view, buildings and spaces which were designed and built based on the requirements of western societies were spreading all around the country [Figure 3 .36], where people did not have such cultural and society structures as in the west. It was a critical time in the history of Iranian art and architecture, when a considerable cultural gap appeared between the character of the users and features of the products. Since locals were not that much involved in the generation of such buildings and cities from the beginning, the vernacular values of the Iranian architecture have faded gradually in regard to the modern buildings and the cities structure. It can be said the designers and planners are still struggling to integrate foreign technologies and systems with the local characteristics in order to calm the cultural shock both in societies and the business of constructing buildings; a complicated problem which is more evident in larger cities such as Tehran, where the lack of personality in architectural products,

Figure 3 .36 Ekbatan

'Ekbatan' residential complex located in the west of Tehran, the capital city of Iran. The mass housing project was started in 1975 and the construction works finished in 1979. Ekbatan is one of the modern urban planning development projects that have been built all around the country from the mid 20th century. The project had been designed by Jordan Gruzen (Gruzen Samton LLP), an American architect. Another American Company called 'Starrett' took over the construction and finished the first phase of it before the Islamic revolution in Iran. Picture (Ekbatan online, 2013).

defines a big issue facing both the government and public (Mohammadzade, 2009).

The Iranian society to a large extent was unable to domesticate the content of modernism according to its local values. Nonetheless due to their simplicity, shallow aspects were emphasized while social and philosophical significances were ignored

[Figure 3 .37]. The depth of developments, the process of changes, and philosophical and intellectual progressions were eliminated, and modernism stepped in by the introduction of imported designs and abandonment of traditional achievements and experiences. According to Katouzian "*In the absence of a comprehensive and coherent thought, and a systematic direction, the progress of modernism in Iran was completely details oriented*" (Katouzian, 1987).

Figure 3 .37 Cultural and technical confusion

'Goldis shopping centre' in west part of Tehran tries to resemble the 'George Pompidou Centre'! One of the things which are expected to be seen in a modern building facade is to exhibit the ideas that reside in the interior or the systems with which the building is built, similar to the 'Original' building in Paris. Most of the elements of this facade are considered as ornaments which do not have any particular function. Picture (Wikipedia-e, 2013).

3.3.3. The manifestation of values in a traditional context

In the past, all aspects of the Iranians' lives in various regions of Iran were influenced by local insight, traditional customs, cultural events, economy, lifestyle, politics and social structure. In addition to all of those above mentioned factors, climate and surroundings were highly effective on the outcomes of the societies in each region. These elements were components of the formation of regional cuisines, fabrics, costumes, music, construction techniques, buildings and urban structures. These differences were so strong that they could be witnessed visually by travelling from one city to another even in the same region [Figure 3 .38].

Figure 3 .38 Cultural variety
Different cultures in different cities in Iran are visually visible. The differences are not just in costumes; each area has its own local foods, music, language and especially architecture
Left: traditional costume of the Turkmen people from south eastern coast of the Caspian Sea. Picture (Fars News Agency, 2013).
Right: traditional costume of the people from Gilan residing in south western coast of the Caspian Sea. Picture (Gardeshpedia, 2013).

Climate

Historically, construction in Iran had been based on climatic and environmental factors that have resulted in the appearance of different styles and methods in different regions of the country, all of which presented a unique approach towards the integration of architecture with the natural environment of the region. According to geographical information, the country of Iran is divided into four main climatic zones including hot and arid, hot and humid, mild and humid, and cold (Ganji, 1955). According to Figure 3 .39 these main climatic zones are divided into 12 sub categories. Consequently, the typology of vernacular buildings especially residential dwellings in each zone are variant, influenced by climatic, geographic, topographic and environmental factors. In another word, the diversity of geoclimatic conditions in Iran has largely contributed to the formation of numerous architectural forms, and construction methods, and creativity in the usage of locally available materials and optimal use of renewable energies and resources.

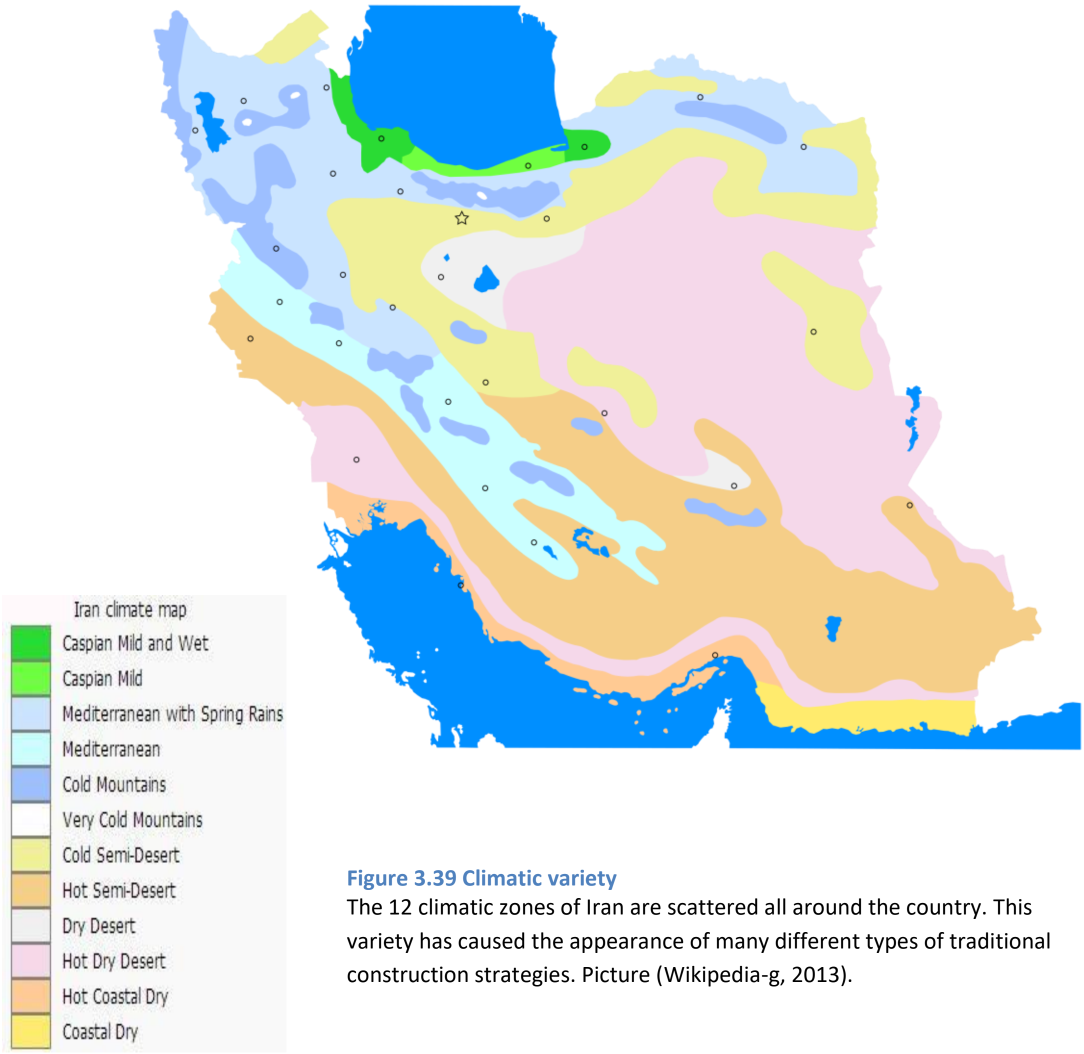
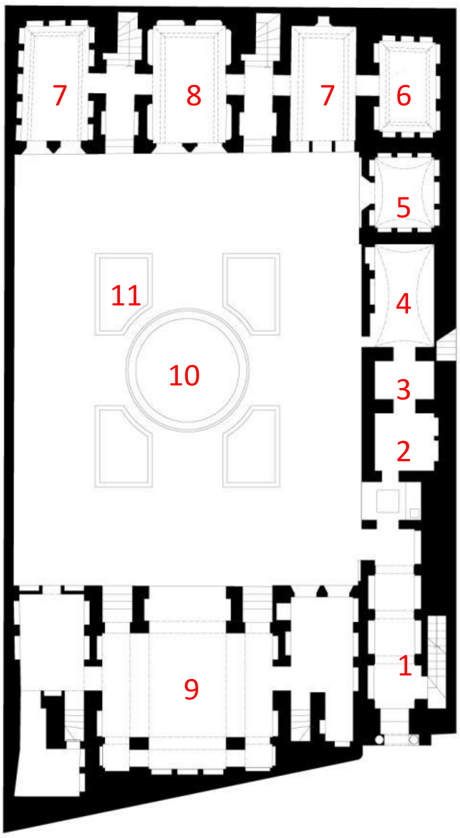


Figure 3.39 Climatic variety
The 12 climatic zones of Iran are scattered all around the country. This variety has caused the appearance of many different types of traditional construction strategies. Picture (Wikipedia-g, 2013).

As an example, in the central plateau of Iran where the harsh desert climate is always accompanied with long drought seasons, water shortage and sand storms have resulted in the formation of the 'inward-oriented' architecture featuring a set of rooms dedicated for different daily activities arranged around a central courtyard in which there were usually a number of plantation features and water pools contributing to the creation of a microclimate inside the yard by maximizing the moisture levels of air, creating shadow and cooling the air [Figure 3 .42] (Monshizade, 2008). The traditional houses of this region have few or no external openings to prevent against the penetration of sandy storms and winds [Figure 3 .41] while the wind towers - as a sustainable cooling system - play an important role in providing passive ventilation and cooling of the interiors [Figure 3 .40](Softaei, 2003). The main building materials are locally available resources such as adobe, brick and clay. Due to their high thermal capacity and heat resistant characteristics, using these materials in the construction of walls and roofs has a direct effect on providing a thermally comfortable indoor space without dependency on artificial cooling/heating systems.

Figure 3 .40 Vernacuar solutions
A 'wind tower' located in Kerman's coppersmiths' bazaar. Kerman is one of the central cities of Iran. Picture (Panoramio).

Figure 3 .41 Cultural and geographical impacts on architecture
In public passage in historical parts of Yazd it is rare to find any openings on the exterior walls of the houses. Yazd is located in central Iran. Picture (Yazd Graphic).



1. Entrance: basically separates the private life of the house hold from the public. The corridor acts as a filter so if somebody comes inside do not have direct view to the interiors.
2. Water reservoir: in the old times water was very scarce in central Iran so it was delivered to each house separately. Thus they had to be placed near the entrance. Reservoirs kept the water clean and cold during warm months.
3. Food storage
4. Kitchen
5. Storage
6. Winter time living room: mostly do not have any opening to the yard to keep it warm during cold winters
7. Bedroom
8. Living room: these places are located far from the guest reception rooms to provide more privacy for the family
9. Reception chamber: is usually one of the closest rooms to the entrance in order to provide easier access for guest and privacy for the family members.
10. Water pool: adds moisture to the very dry air throughout the year
11. Plantation features: provide shade and smoothen the air flow moving towards the indoors.

Figure 3.42 A historical house in Yazd-Iran

The plan demonstrates the ground level of Nematollahi's residence in Yazd. So far 23 different types of house in historical section of Yazd have been registered. This is an example to establish a general view towards the local architecture in the central Iran.

However, in the northern parts of Iran, along the Caspian coast, where annual precipitation exceeds 1,700 mm and the area remains humid throughout the year, a completely different architectural style has been developed which is mainly influenced by environmental factors such as high humidity and continuous precipitation. Living spaces in these buildings are designed to be more open towards the exterior, mostly located in a large plot and surrounded by ecological features; placed with direct physical and visual connection to the outside areas (Diba & Yaghini, 1993). Sloped roofs were widely used all around the top of buildings In order to prevent the permeation of rainwater into the building caused by severe winds. Furthermore, the buildings were built above the ground level to prevent moisture penetration into the building [Figure 3 .43]

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Figure 3 .43 A historical house in Gilan-Iran

A traditional house in 'Saravan woods' in Gilan. Gilan's houses were generally built in large plots allowing the flow of air from all sides to evaporate the moisture. To avoid the moisture to rise from the ground, they are built higher from the ground surface. Picture (Azizi).

Local culture

In addition to the environmental factors, differences in the economic factors and socio-cultural values of different regions have also played a very important role in the design, construction and spatial arraignment of vernacular dwellings.

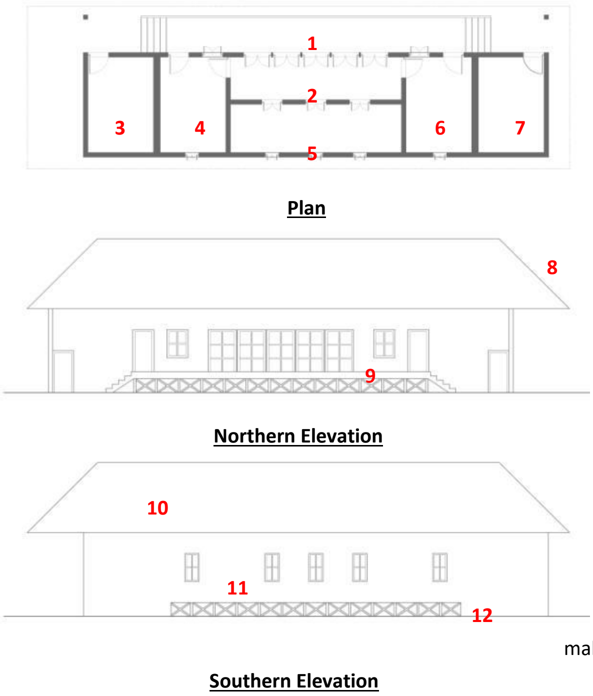
In desert cities, where the economy was based on trade and commerce, participation in the domain of working outside the home and providing for the family was traditionally limited to the male members of the households; women used to dedicate most of their time to perform housework and taking care of children. Due to the nature of their work, men needed to meet, communicate and built a close relationship with their peers and customers through arranging formal or informal meetings and gatherings. Therefore, apart from a place for living, houses were also designed to be as equivalents of today's offices. The need for making peaceful zone for the family as well as cultural and religious considerations have caused the traditional houses to be designed in a way that the privacy of the family being retained by providing separate family spaces including a few rooms providing space for the daily activities such as food making. In that area private life is highly separated from public; therefore the view toward outside areas is strictly limited due to privacy reasons and the interior windows which are opening toward the yard are designed in such a way to let the light in while still preventing from the direct view [e.g. using split and coloured windows]. The female`s living and working areas have a separate entrance and are mostly located at a distance from guest areas where strangers are not allowed to enter. The guest rooms are always decorated with luxury decorations, murals and detailed plaster works (Mohammadzade, 2009).

However, socio-cultural attitudes together with economic activities of people living in northern parts of the country have resulted in the formation of a type of dwelling which is completely different to what we find in desert areas.

Due to the abundance of water resources and fertile lands, agriculture and animal husbandry are considered the main occupations during the cultivation months with fishing, mat weaving and craft making being the main secondary professions. Therefore, the level of household participation in production activities determines the quality and importance of living spaces within the dwellings. In such a society where women are responsible for a great deal of economic activities outside the home, the need for privacy and separation between men and women is minimized, class differences lost its ground and attention to luxuries and decorations is very low. On the other hand, due to the need for frequent supervision and monitoring of the farms, residential areas and livestock, the main living spaces require to provide a direct visual connection with their surrounding areas. Furthermore, since most family members were involved in working outside the house during the day, having a single function space which is being used for a limited period of time is not justified, thus the effort is placed on the creation of multifunctional spaces which can be used for different purposes as needed at different times of the year. For example, the Eyvan -which is a semi opened space- may function as a seating and relaxing space during the summer months or serve as a storing space, children's play space, working space for craft making and mat weaving activities and other family gathering [Figure 3 .44] [Figure 3 .45] (Khakpour, 2005).

Figure 3 .44 Eyvan

Eyvan is an essential building element in northern Iran. 'Arash Mansouri' a local architect has designed and built this house in 2011 based on exact characteristics of the traditional houses in Gilan.



1. Eyvan
2. Room for daily activities with good natural ventilation. A desirable place during warm months.
3. Stable
4. Guest room
5. The area which can be fully closed and isolated from the outside harsh weather by other surrounding spaces
6. Activities such as cooking or weaving
7. Storage room
8. The western side of the roof is deeper to provide support against winds
9. Large openings in outer northern wall to allow maximum fresh air in
10. Gable roof providing maximum rain water drainage. The inner cavity provides room for harvest storage.
11. Southern windows are relatively small. If open, provide smooth air circulation and when closed during winter allow enough sunlight inside to make the room warm.
12. The space between the building floor and the ground allows air circulation which helps to reduce moisture inside.

Figure 3 .45 Typical houses in Gilan

Drawings demonstrate a general view of the traditional buildings in most of the areas around the southern coast of the Caspian Sea.

3.3.4. Paradigm shift in architecture of Iran

In such a context, the traditional architecture of Iran has primarily relied on the compatibility of people`s living and working spaces with their surrounding environment as well as their economic activities, local costumes, lifestyle and sociocultural norms. Accordingly, from architectural and urbanism configuration systems to planning, spatial boundaries and even every single building elements were all designed in accordance to the thermal, economic, social, cultural and individual needs of the occupants. However in the process of modernization, the emerging Western architectural style of the post war period became popular, dominating art, architecture and urban planning of Iranian cities. As a result the destruction of traditional buildings in favour of the erection of cubic, standardized buildings became synonymous with development and progress (Modarres, 2006). Architectural designs, planning forms and buildings facades were completely transformed under the influence of international trends, as traditional methods and patterns were replaced by new ones, climatic and environmental considerations were minimized in the design of buildings while modern mechanical and electrical means were employed in order to provide thermally comfortable spaces within the buildings [Figure 3 .46], instead of the local materials, newer materials such as steel and concrete were popularized and standard building elements, components and materials replaced the customized ones. As a result of such approaches, Iranian cities become devoid of their once dominant architectural identity while the physical and spatial discontinuity between architectural developments and traditional achievements was intensified by the rapid expansion of cities and irrational use of imported features. The 21st century Iran has to deal with a local cultural chaos as well as the lack of natural resources such as energy and water. The excessive use of these resources has caused damages to the environment. After the United States and Russia, Iran owns the 3rd place in natural gas consumption. Electricity consumption capitation of Iran also does not show any promising figures and the country is the 21st

consumer of this type of energy. Iran is also amongst the top 8 countries in the case of producing CO2 emissions (GES Year book, 2013).

Residential and commercial buildings are on the top of the table of energy consumers with 40% of the total energy consumption dedicated to them (Farahmandpour, et al., 2008). The residential buildings sit on the top of the list by using 21.6% of the energy produced (SCI, 2011).

Figure 3 .46 Lost background and modern solutions
Numerous AC units on the buildings' facade show that not only living there is fully dependent to the artificial systems but also even the right mechanical systems have not been designed and used for this building.

Considering the history of the paradigm shift in the Iranian architecture, modernity in Iran was merely manifested in physical and shallow aspects instead of advancing the technological, philosophical and aesthetics features of the buildings and cities. Consequently the majority of contemporary buildings are still being erected using old structural systems and masonry-infilled walls which require a great deal of construction works to be carried out onsite, resulting in a higher rate of waste in production and also during the buildings' lifecycle, a lower rate of work progression and the production of low quality buildings against natural disasters such as earthquake due to the use of heavy materials [Figure 3 .47] (Ghahramani, 2008).

Figure 3.47 Mass produced housing projects in Gilan

Figure shows a governmental project for construction of mass produced housing in Gilan. Apart from the lack of aesthetics, local identity and variety, using old structural systems and construction materials such as concrete blocks and clay blocks covered with stone have made them heavy and vulnerable against seismic activities. Picture (Maskan Bank, 2013).

The government attitude to encourage the industrialization of construction projects was also ineffective due to the lack of construction policies, required infrastructures, scientific foundations and applicable and compatible methods with the needs and existing facilities (Ghahramani, 2008).

Clearly sustainable development in every field is reliant on constant improvement of tools, methods and strategies while having strong link to the past to create basis for later growth, considering the current environmental and contextual factors as well as opening opportunities for further adjustments and progression to update products based on market changes.

Being discrete from its roots, current trends in Iranian architecture and planning requires major betterments in philosophical and technological aspects in order to increase the productivity, reduce construction costs, meet the demands, improve construction standards, improve quality of life, reduce land use, reduce energy and resource consumption, employ appropriate structural systems, reduce the weaknesses of current construction policies and resolve the aesthetical architectural problems that have damaged the face of the Iranian cities in the modern era. It is believed that such changes would be crucially effective if being based on in deep studies with emphasize on socio-cultural, religious, historical, political, geographical and environmental perspectives.

3.3.5. Standardization and uniform products

A general review of the contemporary housing developments in moderate and humid regions of the north and hot arid regions of the central parts of Iran reveals that despite conspicuous differences in their vernacular architecture in terms of form, plan, orientation, interior spaces, construction materials, structure and etc., their houses which are built during the recent years are majorly similar. First and foremost, new urban and building policies, pattern of gridiron planning and reduced size of land parcels have necessitated the formation of high-rise buildings and multistorey apartments instead of low rise, single household dwellings. In addition, the building policies and regulations are on a national scale which means the same building guidelines and strategies are enforced in multiple regions resulting in the formation of similar buildings without any consideration on the local conditions. In this sense, regardless of environmental and cultural factors of orientation and form in vernacular houses, the contemporary houses in both northern and central regions are oriented outward. The Eyvan, as an important element of the northern house, and the courtyard as the focal point of the desert house, have almost lost their meaning and functionality. In contemporary buildings open and semi-open spaces are limited to a backyard (which is a shared space between households) and a small balcony that can only be used for drying cloths, storage and so on. Arrangements of the indoor spaces in northern dwellings have lost their multifunctional characteristics and environmental effects. In a same way, Indoor spaces belonging to desert houses, which were based on environmental and cultural factors, are now squeezed into a small, opened plan apartment flat which confirms that many spaces in the traditional home must have been ignored in the new housing style.

In terms of construction and finishing materials, again, neither wooden material are being used in the construction of contemporary houses in north, nor adobe and earth materials for desert houses. In both regions, masonry-infilled steel and concrete structures are the most common construction techniques where clay blocks, concrete blocks and brick are being used as the main infill materials. Beside fundamental similarities in design and construction of houses, the application of the same insulation materials, building elements (e.g. windows and doors), and ventilation equipment have also contributed in the formation of ubiquitous housing types which are remarkably homogeneous in terms of physical features and environmental responses. Application of breathable materials to build and insulate buildings in the north, are now replaced by tar paper which traps the moisture inside. In almost every newly built building in that region signs of condensation ruining the paint of the internal walls are visible.

Undoubtedly, as time passes, gradually the culture of the peoples in every region of the world changes as do the traditions, lifestyle or even the climatic and geographic features. This is a part of human evolution which includes manmade products. The change is inevitable but what is important in this instance is how production faces the demands, restrictions and possibilities.

Figure 3 .48 Governmental housing projects
Despite all the differences in the architectural and cultural background of the two regions, new developments are becoming extensively similar in Yazd and Gilan.
Top: governmental mass produced housing project in Yazd. Picture (The housing cooperative of Yazd, 2012).
Bottom: governmental mass produced housing project in Gilan.(Maskan Bank, 2013)

From what that can be witnessed in this document it is evident that the lives of people now is experiencing major changes compared to what existed some hundred years ago. Obviously cities have been growing exponentially; people perform jobs that have not existed even a decade ago and have different human relationships.

They eat different foods, they may talk in a different language and many new means of connectivity now exist between peoples in one family, city, region, country or with people in other parts of the world. Technology has opened new ways of solving problems and realizing our dreams. Despite all of the efforts to gather people in the so called ‘Global Village’ based on our commonalities, it is still the differences between people, societies, cultures and locations that makes the world an interesting place to live.

New circumstances define new rules changing the old ways of doing things. Some factors with less importance may become priorities and some previous key elements may lose their values in a newly defined environment but these alternations do not change the fact that it is values and priorities that should define the rules. The same approach applies to the local architecture whether talking about the Britain or Iran or any other country. In this chapter some aspects of the local architecture of Gilan and central Iran have been discussed as an example; yet it can be said that problems with the same roots but possibly with different indications exist more or less in most places and societies in the world.

3.3.6. Possible solutions

So far it has been seen that those construction technologies which have been imported from the west have changed the Iranian architecture systematically and subsequently the Iranian societies culturally. There are some inherent problems caused as a result of this transformation. Nevertheless regarding the most recent trends in construction industry [such as those used in the work of the ‘Facit homes’ described in chapter 3.6] there could be some potential solutions for these problems within the use of the digitally integrated methods and devices.

Although there have been a number of cultural and technological studies regarding Iranian architecture in the past and in the current time; yet, in order to identify the problems mentioned here and to measure their impacts over the local culture and lifestyles, there should be further extensive research commissioned to map the local characteristics of the cities in different regions. These could then be used to identify possible solutions that could form the direction of any future decision making and subsequent actions.

On the other hand there are modern and flexible methods of designing and making buildings which can negate the undesirable conventional methods and move towards a more cost effective, productive and less wasteful system, while making the end product customised, of a higher quality, and more energy efficient. As well as some of the works which are illustrated in sections 3.4, 3.5 and 3.6, there are many more digitally integrated approaches towards efficient, customised and sustainable buildings which are going to be discussed in section 3.7. The intention of most of these methods is to create a flexible and efficient system for the design and construction of buildings; therefore they could be used in many different places, be adapted to many different design approaches, create a large variety of building forms, be efficient and ultimately reduce construction costs.

These flexible systems can also use a variety of local materials to create vernacular forms and spaces while reducing waste and costs and therefore have a more sustainable impact over the surroundings. Such a system accompanied by a sufficient core of knowledge and strategies regarding the past, present and future of local architecture in different regions could be regarded as a way out of the current condition that effects the lives of billions of people around the world.

Part two: Digital technology and industrialised architecture 3.4.

Ultimate Creativity: Frank Gehry

3.4.1. Why Gehry?

Regarding the topic of this research the answer is rather clear. The majority of available documentation which discusses the application of CAD and CAM technology in architecture [that may also refer to it as digital architecture] contains at least one example studying Frank Gehry's works. His pioneering work in the digital design and construction of the 'Disney Concert Hall' as well as many other internationally praised projects all around the world has had a major inspirational impact over the work of many other architects. In a similar way to many other architectural masterpieces throughout history, his projects have become a source of pride for the local community and have rapidly found their place amongst ground breaking monuments which remind us of the first and most challenging efforts in using digital technologies in the building construction industry. His work is known as sculptural architecture and has not only inspired the architecture world in form generation but also has initiated a revolutionary movement in construction and project communication. It is interesting to study how his office changed their work flow and methodology in designing and making buildings at a time when there was no sign of computers in architectural bureaus and also to see how they realized the fact that in order to create unconventional forms and spaces, the essential would be the application of digital technologies.

In many of his projects prior to the Disney Concert Hall in Los Angeles, Gehry had proven to be a creative designer; yet working within traditional design and construction techniques had limited his work to not being that radically and revolutionary different from that of his rivals. Designing the Concert Hall, he embarked on a relatively new path which would change both his career and the architectural world. As in any outstanding project he did not constrain himself to conventional forms which could be built using available machinery and techniques.

It was only after they finished the initial design of this building that the team realized that a technological gap creates a strong barrier which limits creativity in certain areas of form generation and construction feasibility. Being amongst the first groups who have contributed to the new era of technology they had to overcome many problems and sometimes find their way through trial and error. Looking back at the path of Gehry's career it is not a secret that despite all of the bold innovations and the impact on the progression of architecture, many of his projects [including the 'Disney Concert Hall'] cannot be regarded as ultimately successful in all aspects especially in the regard to cost and time management which will be discussed briefly later in this chapter. Nevertheless, being one of the first to try something new mostly means missing out on any previous experiences and examples. Such a process has its own risks; sweet and bitter moments that may change the world forever or turn the project to a complete failure similar to some prefab building projects which have been previously discussed in the history of prefabrication chapter. Many novel features do exist in his projects but when compared with the current capabilities of the digital technologies [even though many of his digitally built buildings are finished only a few years ago] it can now be seen that many aspects could be executed much better or in a completely different fashion; nonetheless despite all of these errors and mistakes the more important factor is the experience which builds the future and having such great projects in the history of architecture makes a reliable foundation for future improvements. In the domain of digital architecture we can say that it is an evolutionary process rather than a sudden revolution, since progress in this field happens through learning from mistakes and the realization of what works and what does not (Smith, 2010).

Each of the three examples in this document has been chosen based on at least one of their predominant feature. As it has been mentioned before the majority of the most recent Gehry projects and amongst them the Disney concert hall are considered as art pieces. The Los Angeles concert hall's extreme uniqueness both in its general form and in the fabrication of every single component that has been used to build such a building has made the process of creating this landmark distinct from the other two types of projects which are going to be discussed later.

Figure 3 .49 Walt and Lillian Disney
Picture (Mouse on the Mind, 2013).

3.4.2. The leap forward

In 1988 Lillian Disney [Figure 3 .49], Walt Disney's wife, funded a design competition for a new concert hall on the Los Angeles Music Centre site. The original fund was $50 million which was granted to the county of Los Angeles (Wilkman & Wilkman, 2008). During the competition they didn't want to choose a design but instead chose an architect who would be creative and responsive to the comments and the characteristics of the site and nature of the function. Gehry's proposal for the concert hall became the winner of the competition [Figure 3 .50] and in many ways it truly has been entitled as a major advance in the progression of Gehry's career and also a significant milestone in the realm of architecture. The Walt Disney Concert Hall was a clear announcement of the emergence of Gehry as an Iconic figure amongst leaders of the Architecture world. This was happening, when Gehry was changing his work focus from residential and commercial projects to a more sophisticated style in iconic buildings (Kolarevic, 2005).

Figure 3 .50 The Disney concert hall proposal

Frank Gehry and the model of his winning proposal for the Disney Concert Hall. It can be seen that the proposal was very different from the building which was built over a decade later became opened to the public (Los Angeles Times, 2013).

It is hard to find any architectural heritage in the area of Los Angeles which is more respected than the 'Disney Concert Hall' [Figure 3 .51]. Many believe that it has the most significant impact on defining the Los Angeles downtown new built environment quality (Gartman, 2009). To obtain these titles Gehry tried to design an external translative form which suggests music (Gehry, 2003). He considered a physical plan consisting of a large public and exhibition area made with glass which is named by Gehry as "*the city's living room*" (Borda, 2003).

Above all of the physical characteristics and advances, what actually makes it a unique design experiment is the enhanced expression of the meanings. The declaration of that "*ideal beauty rarely exists in an imperfect world*". The Gehry's delicate confrontation with this challenge makes Disney concert Hall an exception in social remarks. Although some may call the accomplishment of the construction process as a miracle, since it took 16 years to be built; yet, the success of this project and many others which were completed during this period has confirmed Gehry as among the greatest living architectural talents in United States. These projects are also highly influential on the culture of their locations and communities and initiated a new movement in architectural design and construction (Kolarevic, 2005).

Figure 3 .51 The hall and the city
In contrast with its surroundings, the 'Disney Concert Hall' catches the eyes in the Los Angeles downtown. Picture (arifrc, 2013).

3.4.3. Gehry's design approach

Gehry is famous for the use of physical models in his design projects. This trend stems from his passion for music, painting, sculpting and the arts (Academy of Achievement, 1995). His creative designs could not be developed by just using technical drawings reproduces on a piece of paper. He needed to see his work in the real world and develop it in a physical form so he could realize what the final product would look like before actually making it. The necessity of the physical models in Gehry's work is also due to the pioneering and unique building components and material he uses. As the 'Pritzker Prize' juries on their comments about the reasons why Gehry won the prize they cited that he is always passionate for experimentation and trying new things in his work (The Pritzker Architecture Prize, 1989); thus in some projects he even tends to make full-size prototypes of parts of his buildings in order to test them against the severe conditions of real life (Stuart, 2013).

An example of his design approach can be seen in the process of designing the Disney concert hall. From the beginning, what the design team had in mind was to make an icon, which would acoustically be the greatest concert hall ever made to carry the highest aural and architectural qualities for a supreme musical experience (Mackay & Pilbrow, 2003). Several studies and experiments had been done on existing concert halls and many models of merged designs of them have been built to find the single solution and form which would best suit the Los Angeles concert hall [Figure 3 .52] (Kolarevic, 2005).

Figure 3 .52 Concert hall's form generation
Studies of different concert hall configurations. Picture and description (slideshare, 2012).

Searching amongst the outstanding buildings of the recent few decades we realize that apart from its technical and technological superiorities, the Disney concert hall is one of the most interesting projects of Gehry and also the architecture world because its design started without computers and at the beginning was planned to be constructed without CAM techniques. Nonetheless time taught Gehry to change his methods and follow a new path which would lead to digital architecture. Another reason for it could be that in order to build such a complex building he would need to exploit the power of the computers.

Gehry's office commenced the project in 1989 and the completion of the project took an overall period of 14 years to finish and during this long process, numerous modifications on the building's appearance and construction method can be witnessed. Many factors such as the economy, politics and geological phenomenon [the 1994 Northridge earth quake resulted in the skeleton of the building being changed to a steel brace (Koshalek & Hutt, 2003)] were involved in these changes; yet, the most influential was the improvement of computers from both software and hardware points of view. Although Gehry intended to consider the application of the most cutting edge technology throughout his work from the beginning, but to create an icon he needed more than the technologies that he had applied up to that point of his professional life in 1989. In the early stage of the project, the office was using basic Auto CAD drafted models to make handmade mock-ups. Although his physical models were not so accurate and detailed, others could easily and quickly realize the ideas behind it (Lindsay, 2001). Dr. Toyota, the acoustician of the concert hall, could also use a more sophisticated technology in his work since he was doing ray-tracing studies in order to adjust what they called the modified 'shoebox' for the best sound quality. Lack of technology at the beginning [software, hardware and useful 3D models which could contain the real life features of the material and space] forced Toyota to adjust the reflective panels using physical models which was well-matched to Gehry's working style at the same time. The idea was to use the perfect acoustical form to generate the buildings shape and to do so they had to run a trial and error process (Webb, 2003) (Janmohamed & Glymph, 2004). Initially the team used whatever was lying around the office, even paper cups, to embody their ideas in designing the complicated shapes of the building's physical form. Using physical models enabled the design team to develop their ideas to move towards a perfect form and the development of the sail-shaped volumes has come from these study models because there was no digital modelling. In fact there was no computer in Gehry's office at that time (Kolarevic, 2005).

3.4.4. The design – construction gap

After the formation of the interior spaces and exterior volumes, the designers were confronted with some challenging issues. What method of construction should be applied and from what sort of material should building be built? In the chapter two some general systems of applications of this technology have been defined briefly. We know that apart from extended capabilities in design, form generation and production, CADCAM provides a continuity of design and production which gives the designers more control over the production process. At this stage of his work, Gehry was aware of the shortcomings of the conventional methods which, accompanied by the benefits of digital techniques, could be regarded as a few of the pressing reasons why Gehry needed to make some changes in his style of work. During the long course of design and construction of the Disney concert hall the design team had been asked to present their design and construction strategies on many occasions. One of the most important events was at the Venice Biennale in 1991 when he was working on new design of the building which had been dramatically changed compared to the original design competition's proposal. The second major presentation was at the MOCA's Plaza in Los Angeles from October 1996 to April 1997. The participants in both exhibitions could see radical changes in Gehry's method of work. In 1991 they could only see the work which was based on hand drawings and CAD/CAM produced representative models of the curved stone walls were originated from physical models, rationalized by 'CATIA'; while in 1996 they saw the project which was fully based on digital technology to demonstrating a more accurate, affordable and feasible plan for the building.

Before the first exhibition in 1991, in order to connect the office to the factory they produced a CATIA model of interior spaces in addition to the stone and glass exterior walls. The detailed model was originated from a rough digital model which was made by applying reverse engineering tools such as a digitizer arm to scan the existing physical models. The challenging task for the team was to determine the feasibility of the curved surfaces which had to be covered by stone. They also had to consider some rules about breaking the surface on the curves and there were also certain constraints on radius and arcs on the diverse 'flips' of the exterior surfaces. Conventionally, curves had to be made by repeating the same shape of stone blocks along horizontal and vertical lines between the blocks which was not what Gehry expected from the facade. In some cases a curved surface could be broken into many quadrilaterals. These polygons would indicate the breakpoints of stone blocks that were supposed to cover the exterior of the building. In some other cases they kept the curves in the original design, since they were already aware of milling technology which could produce individual curved blocks of stone. Horizontal shear joints caused the building to have a certain amount of movement in the event of earthquake in order to be responsive to the seismic features of California. Gehry designed a connection system in which each stone would be supported individually, thus it could move independently to absorb tensions; consequently, stone walls could move slightly without having each connection working as a moving joint and there was no need for large joints in between stone blocks which would ruin the unity of surface (Janmohamed & Glymph, 2004).

After running several tests on the model, they finalized it and prepared a comprehensive model. The negotiations began with Italian companies to fabricate stone blocks based on the digital models using CAD/CAM techniques. Although they intended to use digital technology, the basis of their work was still rooted in traditional methods of form generation and draughting. It was possible to finish the project that way but the result wouldn't be perfect due to the errors caused by merging traditional design and modern fabrication methods.

The project halted very soon thereafter. The project's budget was surveyed in detail by which all costs were calculated on a component based criteria. They had considered all the technical and economic aspects of constructing the Concert Hall with stone-made surfaces. At the time the team was developing 2-dimentional drawings using traditional methods and only 10-15 percent of drawings were left to finish this job, they then found out that construction of the proposed design for the concert hall containing such complicated features that it was technically impossible by applying traditional methods. By raising doubts on the feasibility of construction, the failure of the preparation of drawing documents and the inefficiency of traditional elements of construction methods caused an unprecedented suspension of the work on the project. The ongoing processes in all teams were stopped when nobody could imagine a clear future for the building (Kolarevic, 2005). Michael Webb in his essay about the progress of the Los Angeles Concert Hall in 2003 mentioned that:

"*Had everyone rallied behind the project and the necessary funds been raised, the original design [or its immediate successor] could have been completed by 1993. The Los Angeles philharmonic would have been delighted, and the world have applauded, as it did when the Guggenheim Museum Bilbao opened in 1997. But the Concert Hall would have fallen far short –aesthetically and acoustically- of the masterpiece we have finally gained"* (Webb, 2003).

Forms which were emerging on physical models were unique. Gehry was always struggling with the border between architecture and sculpture to balance the building volumetrically. Although the building's functionality and its role as an urban element ruled as fundamentals of design, but the free flow of forms on the exterior façade of the building was not such a thing that we expect from a building but perhaps from a sculpture. Working on the construction concept took them to the point where they embarked on several studies regarding the application of upcoming digital models and CAD/CAM technology, among them CATIA, to measure the feasibility of their design proposals to be constructed (Mackay & Pilbrow, 2003). Although Gehry had always used physical models in his design projects yet in the case on the concert hall one of the greatest needs for a scaled model of the hall was firmly related to the measurement of the effects of echo which is a critical element of sound in concert halls. At the beginning, there was not any proper ray-tracing software to fully measure reverberation so they had to do the hard job and make a scaled-model [one to tenth] and fill it with nitrogen to reduce the density of air in it [Figure 3 .53] (Webb, 2003). Using high frequency sound, to simulate the space and using test results to develop the design. By taking all these steps they were sure that all the risks have been recognized and necessary actions were taken to exhibit a perfect design in the 'Biennale'. In order to make these models they used CADCAM techniques; yet later some digital models which were capable of simulating the auditorium in real life were produced. These models helped them to figure out some problems which they were not aware of before and could fix them in the way which was not possible without computers. Digital models also helped them to make changes in the internal surfaces by keeping the same acoustic and aesthetic quality but helped Gehry's team to plan the system of construction.

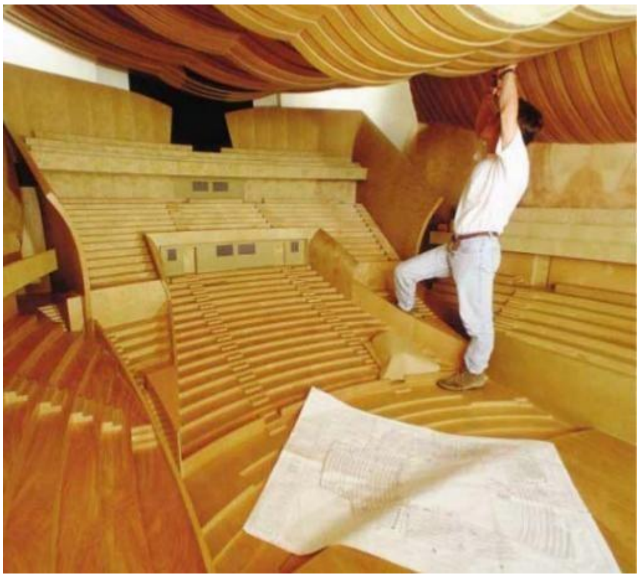


Figure 3 .53 Acoustics Study
Acoustics team made large-scale models to test the echo effects in the Auditorium. Picture (slideshare, 2012).

Gehry managed to turn his failures to a key moment in becoming what his office is most known for; what they are now, the pioneers of using digital data in building construction which began to spread all over the world from early 90's. It was such a sharp breakthrough that it was not easy for everybody to come along with it and break the taboo of fundamental changes in the way of architects thinking and designing. This paradigm shift happened through acquiring new computer applications and raising the number of staff to more than double; basically to use specialists in the realm of digital to change the game, using digital models and techniques all the way through the design and construction process [Figure 3 .54] (Koshalek & Hutt, 2003).

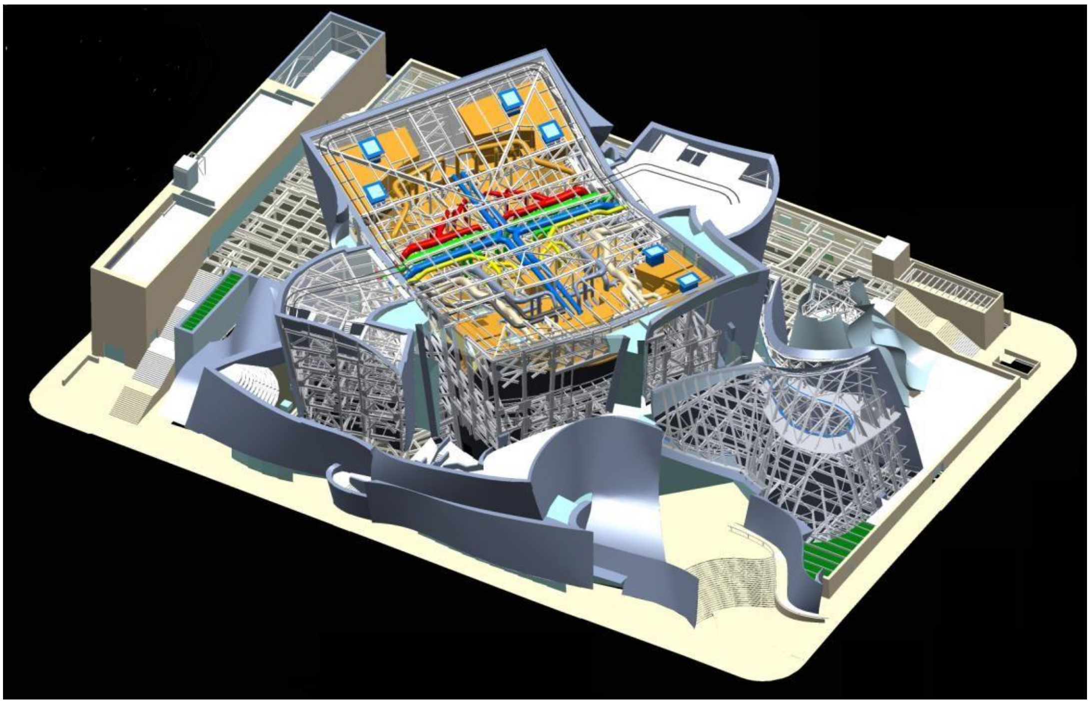


Figure 3 .54 The structural model
CATIA model of the structural frames of the Concert Hall. Picture (Virtual Build Technologies, 2010).

3.4.5. Practice makes perfect

Despite the fact that Gehry designed the concert hall to be built of stone but frustrating 2D drawings and unresponsive traditional construction processes put a large question mark to the feasibility of the project. Simultaneously, they started to do some paperless projects such as the 'Barcelona Fish' [Figure 3 .55] which made them believe their adoption of 3D digital environment was the correct choice. The 'Fish' was a rather smaller project, consist of a cladding on structural steel, but what made it special was that only 6 hand drawings were produced and the whole process was being coordinated through computers (Lindsay, 2001). The Barcelona project was an experiment, a good start for latter projects. Through that project they became proficient at extracting fabrication data from a digital model and transferring it to CNC processes. They also learned to communicate with contractors by using the same database. In other words they used computers to design, prepare the layout of system and to track components.

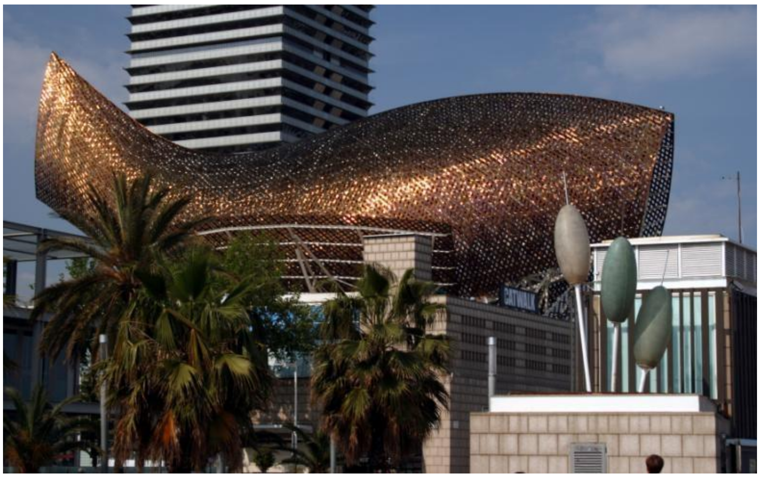


Figure 3 .55 The Barcelona Fish

Gehry's Barcelona Fish built for 1992's Barcelona Olympic Games. Picture (Turner, 2009).

Soon after the concert hall project halted they started another project in Prague. A complicated form made of steel and glass known as the 'Internationale Nederlanden' [Figure 3 .56]. Superficially, it looks similar to nineteenth century buildings which basically were made of steel; yet, the story of the structure below the skin of the building is totally different. It was basically modelled by computer from which they could make casts and use CAD/CAM to produce precast concrete components. Since there were slight differences between various parts and labour costs were so low there, they transferred the fabrication data to craftsmen who hand built the casts (Kolarevic, 2005).

Figure 3 .56 The dancing house

'Internationale Nederlanden' or the 'Dancing House building in Prague-Czech Republic done by Gehry in 1995. Picture (Ercolani, 2013).

The order of events was moving fast. The two projects in Barcelona and Prague were finished at a time when the concert hall project was almost stopped. Although

Gehry delivered these projects on time and on budget and after all those experiments, he was able to construct the complicated forms of the building but he couldn't start the project over since a decision had to be made by the committee and funds were not in place. After these two projects, he had a great opportunity to try a novel milling technique in a new project which was placed in Dusseldorf and is known as the 'Neuer Zollhof' [Figure 3 .57]. It also gave him a chance to work with a German contractor from the initial stages of the design process. While the office was experimenting with techniques to connect the computers of the office to machines in the factory to extract fabrication data from digital models, the contractor set up a new machine in the factory which could mill large blocks of foam to make moulds to produce precast components of the building.

Figure 3 .57 The Neuer Zollhof The 'Neuer Zollhof, building finished in 1999 located in Dusseldorf-Germany. Picture (WikiArtis, 2012).

Amongst all of the projects they had completed during that period of time, the Guggenheim museum in Bilbao [Figure 3 .58] plays a key role on the progression of Gehry's work. Finishing this project, they could prove that what they want to construct as a concert hall in Los Angeles is now actually feasible. Now they were able to plan a CATIA model to control the major part of the construction process. The structural designer of the project used curves to reinforce the structure. The other major facilitator was the innovation of Bocad; software which is used to develop steel structures and also could link to CAD/CAM equipments. Bocad delivered some new capability of the computers to make significant steps towards the construction of the Disney concert hall (Gann, 2000).

Figure 3 .58 Guggenheim museum
Guggenheim Museum in Bilbao-Spain finished in 1997. Picture (deviantART).

Generally the two projects in Bilbao and Los Angeles were highly influential on each other in many ways, to be designed and constructed and of course bring success to Gehry's office. Basically they were fortunate to be able to realize what they had in mind for the Disney concert hall project. Local authorities and public regarded the Guggenheim as a 'point of regional pride' and they had faith in Gehry's work and had faith on Gehry's specialties (Bruggen, 2003). Apart from this positive energy input to the office, Gehry was also lucky because he could use the technology which was already provided in the region. He could orchestrate a system in which all sectors would work synchronized to finish the project. By finishing this project they could prove the feasibility of the proposal that they offered to the county of Los Angeles. The recession in Spain and the drop of the global price of titanium kept overall costs of the project low (Webb, 2003). A large portion of success in this project is due to good collaboration with the city council and the Guggenheim with Gehry, respectively as developer, operator and architect. Nevertheless all of those constructive cooperation and support could not be fruitful if they had not used CAD/CAM which not only guaranteed feasibility of complex forms, but also helped to reduce costs in many ways. The great advantage of CAD/CAM was realized not only because of the tools; but also, in the ways which designers and fabricators worked together through the use of digital techniques. Promising results in the Bilbao project triggered a revolutionary change in the progression of the project in Los Angeles. The city decided to start over. This time with more hope and faith on Gehry's work.

The Northridge earthquake revealed the weaknesses of the 'moment frame' structure system which was then popular in Los Angeles. They were ready to start the construction work, but instead they were obliged to redesign the basic structure to meet the new seismic criteria ruling all projects in California. In addition after the completion of the Guggenheim, the supervision committee of the Los Angeles concert hall was not against metal cladding on the building's façade anymore and since Gehry always wanted to use metal cladding in this project, the proposal faced new major changes. Although using steel instead of stone would save over ten million dollars in the project budget; such changes needed time, workforce, redesign, reassessment and reproduction of construction models, consequently some extra charges have been forced onto the project (Webb, 2003). Nevertheless they could reduce the weight of the building by swapping stone blocks with metallic panels. Gehry also had to deal with relatively simple steel surfaces but he was still struggling with unfolding metal sheet and to develop the panels. Similar to many other cases, Gehry got inspiration from his experiments in design and construction of some older projects [in this case the EMP building] to solve problems in his other projects.

Although Forbes magazine entitled it as one of the world's ugliest buildings (MobileReference, 2010), but the EMP [Experience Music Project] paved the way for the concert hall's exterior walls material converting from stone blocks to metal sheets. In EMP they witnessed the quality of metal sheets on different surfaces with various forms [Figure 3 .59]. The office was getting used to the new way of design and construction. Every individual project created a special and unique part of their knowledge about this process. They also shared knowledge with constructors and fabricators so they could have better integration to this new method in building architecture. In EMP, all parties were using one database and all information could be extracted from digital models. Everybody had to know that the time in which an object should be measured by either tape or ruler has past. During the last phases of the EMP, Gehry been asked to design the interior of the café and the wooden façade. At that time designers assumed the construction of the internal curvilinear forms would be the most expensive part of the project. They were short of time and the opening was so close. Therefore the decision had been made to use polygons instead of free forms. After negotiating with the contractors, Gehry realized it would be much cheaper if they used curvilinear forms. In order to save time, they hesitated to make shop drawings and the fabricators made components using digital models and assembled parts on site to make complicated forms without any mock-ups. That part of the building was built in only four weeks. All the people involved in this project had been adapted to the new system. There were no paper documents and it was much faster and less expensive. These changes were not all because of the software they were using, but also due to the cultural changes happened on the construction site (Kolarevic, 2005).

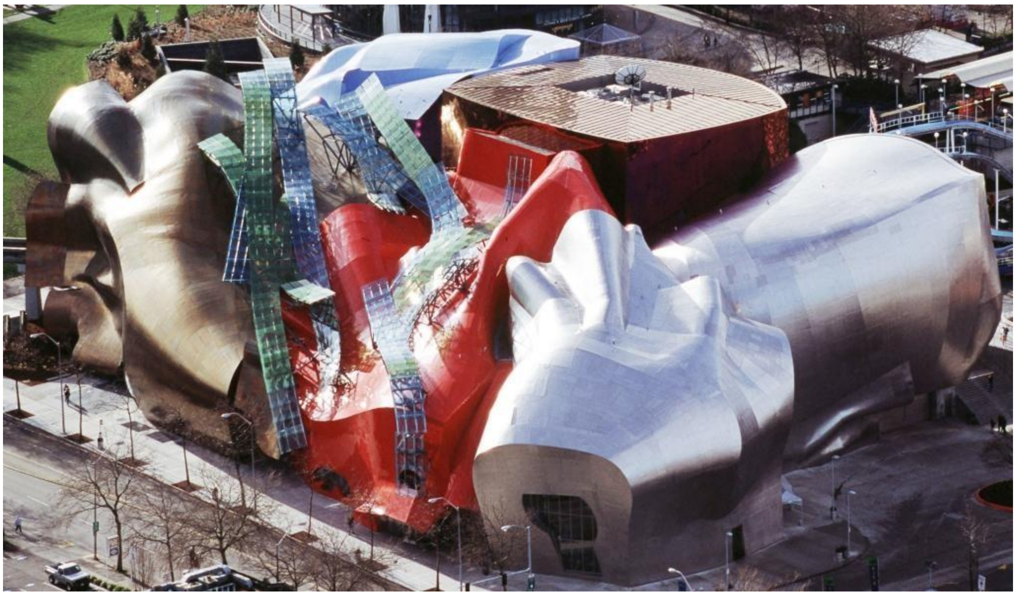


Figure 3 .59 The EMP The Experience Music Project or EMP in Seattle-US finished in 2000.
Picture (2b+3s, 2009).

Similar to the EMP, the Disney project has a curvilinear façade which was redesigned due to the material change on the exteriors. In order to adopt the new material, the curves had some slight changes to better deal with the flow of metal across the curves. The interior remained untouched but the 'brace frame' structure between the interior and exterior had to change in order to match the new criteria implying higher load bearing measures. This way they had to do more detailed work on the steel structure and make more digital and physical models (Garcetti, 2005). Gehry kept the original shoebox as the acoustic hall but what had changed was that after all those years of improvement in digital techniques he could now measure the building's features more accurately. Designers could analyze and improve the hall acoustically with new software and put an end to many doubts over the performance of acoustical elements of the hall. It actually helped them to add some reflective walls and improve the quality of sound for the few seats which have not been served the same as the other seats with the highest standard of sound. In the figure below a list of most influential projects, improving the design and construction of the Disney Concert Hall project has been demonstrated.

Project	Year	Used Technology/Innovation/Improvement
Barcelona Olympic Fish	1992	Paperless design and manufacturing. Finished on time and on budget.
International Netherlanden	1995	Digitally designed steel structure/ digitally produced concrete casts. Finished on time and on budget
Guggenheim Museum	1997	Design and construction of extremely complicated free forms using CATIA. The use of Bocad to design the steel structure. Feasibility of the Disney concert hall design proposal has been proved.
Neue Zollhof	1999	Use of milling machines to make concrete casts out of foam blocks
Experience Music Project	2000	Experimenting with the application of different types of metal cladding on various forms of external façade which facilitated the transformation of the concert hall building's façade from building by stone blocks to metal clad. Creation of a central model of the design which could be access by all groups.

Figure 3 .60 Gehry's Project timeline in an 8 year period

The table demonstrates some of the Gehry's projects in the period between the start and finish of the Disney Concert Hall. These projects and the innovations occurred during their design and construction phase have been highly influential on the success of the concert hall project.

3.4.6. Creating a new path

While Gehry's office was getting more and more experienced on their field of work as digital architects, their way of work was also getting more and more sophisticated. Their work on the Disney Concert Hall project realised numerous changes compared to the process they followed in the Bilbao project. Gehry was ultimately more aware of what he wanted and what his team had to do to build it. They were wondering if the process they used in Bilbao was applicable in the United States. They even considered the possibility of working with the same fabricators as in Bilbao. Evidently by the time that Gehry's office knew what they wanted and how to execute their concepts but finding a fabricator which was able to connect to them was a hard job since they were presenting a pioneering design in every aspect. After several tries with different companies they ended up creating a group of structural and construction detailers where one was working on manual drafting, one was preparing 2D AutoCAD and two were working in 'X Steel', a software specialized in steel structure design. After that time the connection between these groups was not very well organized therefore the sequence of work didn't follow the timetable and the steel work became a bottleneck to the schedule of the whole project (Kolarevic, 2005).

Entrenched working practices, dominant within California's construction sector were creating a barrier against performing as a successful team and repeating the same accomplishment as Bilbao and Seattle in Los Angeles. It was hard for companies to forget about the traditional process and to communicate to each other. In Bilbao all sectors could work on the same model and develop the whole project; while in California they had to start over or move backwards and groups of personnel could not adopt a collaborative process even though it had worked flawlessly in Bilbao, five years before the concert hall project was revived (Glymph, 2005). Although there were many improvements in CAD/CAM process [modelling, software and fabrication machines] still the limits of communication made all these improvements rather clumsy. Despite all the challenges and setbacks it finally worked and the steel structure was fitted precisely.

They designed the external layer of the concert hall's ceiling [Figure 3 .61] to complete the acoustics system but they did not know how to build it. Each panel on the ceiling surface consists of three wooden layers all of which are twisted and curved in different directions (Webb, 2003). They had executed almost the same forms in the EMP but with metal. To run an automated fabrication system, Gehry's office worked with the 'Zehner' Company. Whereas Zehner used 'Proengineer', the architectural office used CATIA; but they were able to successfully establish a good communication system between the two of them to transfer data. Using computers with direct connection to the contractor, they were able to design and fabricate wooden parts to panellize the ceiling. They could determine the complexity of the design and furthermore it was possible to model light fixtures and develop every single panel and establish the position of hangers and adjustment connections. This system presented a high standard and precision of parts [one sixteenth of an inch] which resulted in a faster construction and a high-graded result (Glymph, 2005). In order to automate the whole process for all the panels, they worked with the contractor and the acoustician. The metallic sails of the concert hall were raised without using measuring tapes using only the control points extracted from the CATIA model. The pattern of the metallic panels, sequence of fabrication and delivery of parts and construction, all were synchronized in a 4-D model that the contractor designed based on the CATIA model of the building prepared in Gehry's office showing details of the building in every aspect to seven decimal points (Webb, 2003).

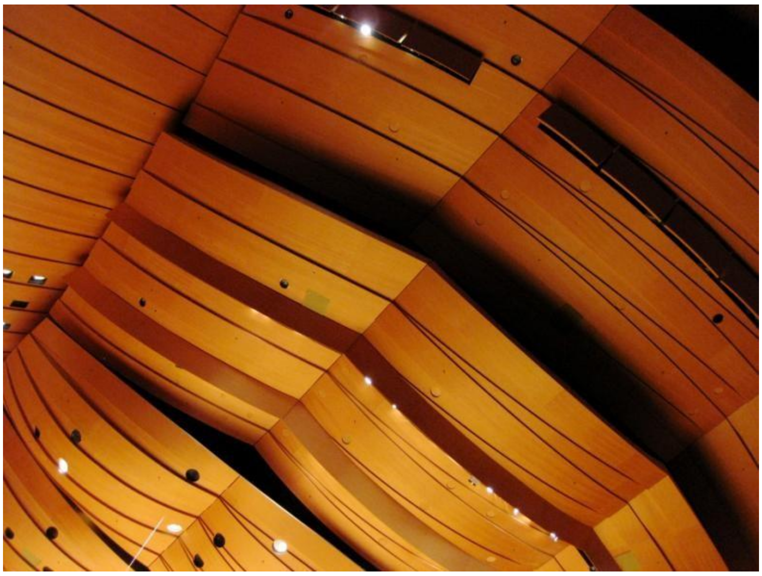


Figure 3 .61 The hall's interior design
Ceiling panels of the Concert Hall. Picture (hullam, 2010).

Since every job applies various resources and technologies, using digital techniques in numerous projects assisted Gehry to experiment and gather knowledge about different aspects. After passing the disappointing confusion in the first years of the concert hall project and the successful completion of many projects all around the world, he was confident enough to apply unique ways to solve problems in many cases. All this work and processes may be slightly different from one project to another. But it can be witnessed that some solutions were useful in various cases. In other words the Disney hall project benefited from many projects that Gehry did from 1990 to 2003.

To bring the ultimate accuracy to the project each unique part of the cladding panel was detailed to a very high level. All the positions of the connections and hangers were accurately marked on concrete slabs. Even though they were not very necessary because of the high precision of fabrication, positioning and construction, fabricators and part designers left plenty of space for adjustment of parts and connection. All parts were coded and numbered and the cladding process developed faster than they assumed (Webb, 2003). Nevertheless they were not sure if time saving at this stage could cover the time they spent on precise engineering.

It can't be claimed that what we have now as file to factory process is a fully automated process. In the exterior of the Concert Hall the last parts of the cladding still has to be cut by hand. Some materials are also not yet compatible with the automated mechanism and new forms appearing with digital techniques. As an example we can indicate the glass work in the Bilbao project, were fabricators had to break the glass around the curves which basically was segmented in the original design. In Berlin project where Gehry and 'Schliech' were working together, Gehry wanted to use more radical free forms while 'Craig Webb' and 'Schliech' were dragging him towards less complicated forms which were easier to calculate and build (Glymph, 2005). The lack of responsive technology could be a major reason for not building more complicated forms. In that project they also started detailing the cladding system based on using adjustable connections but later on realized that it was much cheaper to make each unique connection out of a solid stainless steel block rather than using adjustable connectors.

In many of Gehry's projects he tried to disprove the idea which claims that in order to finish a project on time and on budget, the designer must use traditional elements to produce a complicated form. Consequently they studied factors which would optimize the process and reached some innovative results.

The office developed automotive software which could design an optimized pattern for determining cladding panels on free form surfaces. By changing the form of the surface the pattern would change automatically. It also allows manual manipulation of pattern. These manual changes could be applied on the length of panels in the case of curves getting shorter, longer, smaller or larger. What they did was to prepare a pattern based on what Gehry designed aesthetically; on the other hand they had an optimized rule-based model prepared from a CATIA surface model. A computer runs a parametric analysis to make the two patterns as similar as possible. The fact is that the manual development process and the optimized process to create patterns use almost the same amount of time to achieve a pattern, but the manual process allows the direct impact of the architect to have more idealistic results in a shorter period of time based on the aesthetic values he has in mind (Glymph, 2005).

This outline mostly demonstrated numerous impacts of the improvement of digital technology and the progressive presence of computing in construction on the Disney concert hall project. Building architecture and the construction industry obviously did not benefit as much as other industries did by applying the digital technology.

The revolutionary tendency of using technology to make new forms in buildings exists, but changes take time to happen. Similar to other phenomenon happening around the world cultural changes occur at a much slower rate than technological developments. New ways of designing and constructing buildings not only build new buildings with new forms but also seeks new means of communication, data exchange, planning and contracting.

3.5. Extreme Efficiency and productivity: the 'Broad Company'

3.5.1. Why the 'Broad Company'

The desire for extreme creativity and the creation of a unique sculpture to celebrate the presence of digital technologies, defining new rules of form generation and opening a new realm of thinking and constructing buildings that eternized 'Walt Disney', 'Gehry' and the Los Angeles Concert hall has been shown previously.

The convergence of digital design and fabrication approaches which have been discussed in this document also includes a case especially dedicated to the efforts to bring extreme efficiency and optimization into the building construction world. Regarding the level of modern technologies used to deliver such qualities in buildings, the T30 [Figure 3 .62] as an extreme case can be a good example in showing how design, construction and lifecycle of a building can be realised by digital tools.

Figure 3 .62 T30A The 'T30A' Building in Hunan Province - China. Picture (Malaysia Retail News, 2012).

After dominating the world market with their textile and agricultural products the Chinese economy gradually expanded to dominate more sophisticated industries such as electronics, car manufacturing and modern building. Claimed to be the fastest built and the most efficient construction project, the T30, designed and built by the 'Broad Company' without any doubt wins the votes for extreme performance and economic based project by a large margin. The following part will try to investigate work of the 'BSB' in construction of their fast-built tall buildings. It can be witnessed that in contrast with the previous case [The Disney Concert Hall] they gained efficiency but had to sacrifice aesthetic and architectural values.

3.5.2. Introduction

From the early days of the human history, when societies were formed and our ancestors tried to improve their lives by building shelters and villages, even the small governments of that time were aware of the value of architecture and the quality of built environment to demonstrate their power. Many of the ancient empires are known by the great cities and buildings which they had built at their time of existence. Evidently the same trend still stands as countries, companies and even people try to emphasize their financial, technological or political wealth by designing and building technically and geometrically complicated artefacts. China as a relatively new country amongst the global economic super powers of the new century is not an exception. Each year we hear about record breaking new construction projects such as bridges, tunnels, stadiums and buildings being delivered to clients in China [Figure 3 .63]. Based on these buildings' features, many draw the attention of the world by delivering new qualities to the definition of form, space and construction systems.

Recently a multi storey hotel project has been all over the news due to its revolutionary construction features. On the New Year of 2012 although most of the people were enjoying their holidays and attending their family events, a breathtaking video clip which had been broadcasted over the 'YouTube' reaches millions of hits (differentenergy, 2012). It was the 'T30' time lapse video showing the progression of a construction project in a fast forward motion with a counter clock on the bottom left of the screen showing the impressive speed of the construction process which amazingly stops at 360 hours when the construction of the 100 meters tall building finishes (differentenergy, 2012) (Broad Group-a, 2012). The tower hotel building project which is also known as the 'T30A' is one of the greatest examples of efficiency in construction projects granted by the application of prefabrication systems and digital technologies. Therefore The Broad group which executed the project became the centre of attention even though they have not had a long history in regard to their construction projects. The T30 hotel is situated in Hunan province near the 'Dongting' Lake, a 30 storey building with 17000 m^2 of area is one of the BSB's currently realised buildings and one of their most recently finished projects (Broad Group-a, 2012).

Figure 3 .63 The Beijing's national stadium
Beijing National Stadium opened in 2008 to appear as an icon during the 2008 summer Olympic Games. Picture (Wikipedia-f, 2013).

The Broad group was founded 25 years ago in 1988, focusing on air conditioning systems and buildings' mechanical systems, and became one of the dominant brands in this area of activity (Hilgers, 2012). The Broad Company's policies toward producing environmentally friendly products have led them to the use the reduction of waste and recycling to become the predominant trend in their production framework and products. In 2011 Zhang Yue [Figure 3 .64] the founder and chairman of the Broad Group has been awarded the 'Champions of the Earth Award' by the 'United Nations Environment Programme' due to his efforts to produce environmentally friendly strategies and products (UNEP, 2011).

Figure 3 .64 Zhang Yue Zhang Yue the founder and chairman of the Broad Group. Picture (The New York Times, 2010).

During the last decade they have been expanding their field of activities believing that in order to make the most efficient buildings the strategic concepts need to be designed from the beginning with all structural and mechanical services, insulation and used materials matching and complementing each other. So why not design the whole building ourselves and match everything from the beginning, instead of designing parts of it when because of the constraints caused by previous works it is not possible to get the most optimized results? In 2009 the Broad group established their construction branch called the 'Broad Sustainable Buildings' or the 'BSB'. The company specializes in large scale commercial buildings that are highly efficient through prefabrication (Broad U.S.A Inc., 2010).

Buildings are responsible for about 40% of the global CO2 emissions and have a large contribution to global warming (UNEP, 2009). They claim that the BSB's strategies can reduce the carbon footprint of buildings in some areas by up to 1/10th of the current emissions just by increasing the wall insulations and using multiple glazed windows. To control the largest share in energy waste which was caused by un-insulated buildings the BSB strategies can also be applied on existing buildings. Such an operation doesn't need complicated technologies and basically can be done by unskilled labour. It is so efficient that all the costs paid for the building upgrade can be saved throughout three years of the building lifecycle by saving on energy bills. In this way not only do users pay much less money for their energy usage, but also new systems can provide a better standard of living and more comfortable living environment for users while 80% less energy consumption can lead to a cleaner environment and less danger for the environment.

In addition to wall insulation and the use of multi glazed windows, using intelligent external shades on windows and heat recovery systems have also been highly influential on the effectiveness of the building upgrade. In their experimental projects they have used 15 cm of polystyrene foam board for wall insulation blocks which can be normally installed after only a week of operator training. Using the triple-paned windows made with plastic frames BSB could reduce the heat transfer by up to 1/8th compared to regular aluminium framed windows. The mechanical heat recovery systems have also been highly influential. Up to a 90% rate of recovery in different seasons has made them an inseparable part of the system to reach towards the intended goal in building efficiency (Broad Group-b, 2009). By a quick review of the building even by the public's standards it is clear that the building simply did not try to revolutionise architectural forms and aesthetics; an ordinary cubical Building made with common building materials is the result [Figure
3 .65].

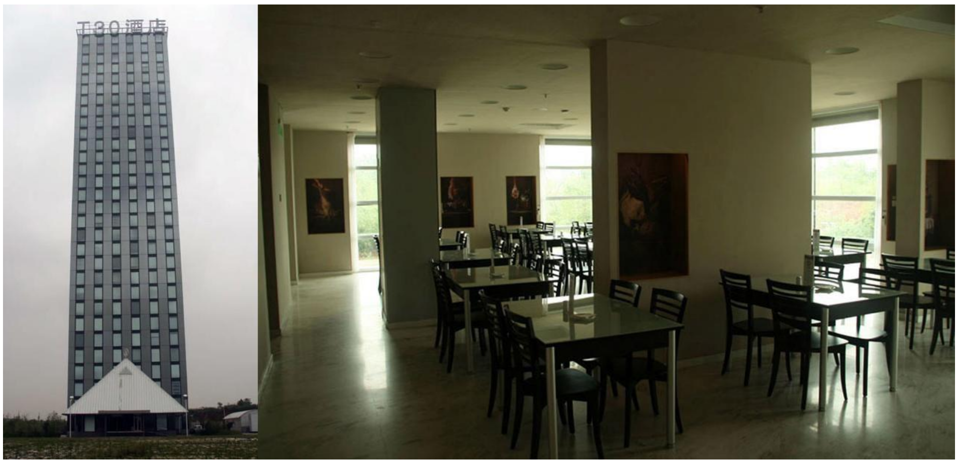


Figure 3 .65 T30A interior and exterior T30, an ordinary looking building inside and out. Pictures (The Skyscraper Center). In fact what is revolutionary in this project and the others similar to this one are the building systems. By looking into the project we see pioneering structural systems, cutting edge testing and building evaluation techniques, modern mechanical devices, highly optimized and efficient insulation materials, precise and effective construction details, highly efficient and quality fabrication and importantly seamless construction planning and execution, all gathered together in order to build the T30 carrying its distinct features.

3.5.3. Sustainability and efficiency

It is understandable from the name of the company [the BSB is initials for the Broad Sustainable Building] sustainability has to be one of the chief pillars of the planning and production of buildings in their projects. According to the company’s publications about the T30 project, sustainability of the tall tower results from eight major approaches to the building construction which are earthquake resistance, energy and natural resources conservation, air purification, durability, material saving, recyclable construction materials, construction materials free of formaldehyde, lead, radiation and asbestos and no construction debris, dust or wastes namely. It is also claimed that the building has used all the above mentioned factors to the extreme which is allowed by today’s technology and in many cases limits have been stretched further for better results (Broad Group-c, 2012).

Earthquake resistance

The great Sichuan earthquake in 2008 which is also known as ‘Wenchuan’ earthquake measures at 7.9 magnitude in which 87,150 people were killed and went missing(BBC, 2013) has triggered the BSB Company’s initiation. About 12 months after the natural disaster, over three hundred scientists and researchers had been commissioned by the Broad Company to research options and run tests in order to design new structure systems which can be more resistant in the event of earthquake compared to other existing building structures (Hilgers, 2012). In the end the research and design teams proposed a new system which is a combination of steel structure and diagonal bracing and offers an overall light weight to the building [Figure 3 .66]. The academy of building research in China ran numerous tests on the structure system to study its performance accurately. To do so they made 7 storey and 30 storey physical models at the scale of 25% and 10% to simulate the impacts of deformation. The results showed that this newly designed structural system performs between 3 and up to 12 times better than other existing buildings of different types of structure [Figure 3 .67] (Broad Group-c, 2012).

Figure 3 .66 T30A- structure

Exposed part of the new structural system visible in the interior spaces. Picture (The Skyscraper Center).

中国建筑科学研究院

Earthquake Resistance Test Conclusion of 30-storey BROAD Sustainable Building

30-storey BROAD Sustainable Building (BSB) is a new structural system designed and developed by BROAD Sustainable Building Co., Ltd, which is made of steel and diagonal bracing structures. Entrusted by BROAD, China Academy of Building Research conducted scaled simulation earthquake resistance test on this structure. The simulator is designed by our academy at a scale of 1/10, and produced and set up by BROAD.

The test was carried out on May 6, 2011 at the State Key Laboratory of Building Safety and Environment of China Academy of Building Research (CABR) according to Specifications for Seismic Test Methods (JGJ101-1996).

30-storey BSB experienced 42 times of simulated earthquakes with different amplitudes in total, using 3 earthquake waves (natural and artificial waves). Tests showed that under the common earthquake intensities of 7 magnitude, 8 magnitude & 9 magnitude, no obvious damage occurred to the main structure. After the rarely-occurred earthquake of 9 magnitude (0.6g), the overall structure did not collapse.

Details and suggestions can be referred to the test report.

China Academy of Building Research

May 6, 2011

Figure 3 .67 Academic research on the T30

A 30-sotrey model of the T30’s structure which has been used by the ‘China Academy of Building Research’ to run seismic tests and issued a certificate approving its durability in the event of harsh earthquakes. Picture (Broad Group-c, 2012)

Energy and natural resources conservation

Undoubtedly energy saving is one of the most important strategies to save the future of our planet. It is also very important for the economy of products. Nonetheless, in many products and chiefly in buildings it is also important to save energy and provide the standard level of comfort for the users. The Broad Sustainable Building Company has applied over 30 various types of energy saving strategies in their buildings and their constructed buildings are claimed to be five time more energy efficient than other conventional buildings. Most of these strategies are not that complicated and it is the accurate calculations and comprehensive planning which have made their use so influential in the company’s products. Ideas such as using effective thicknesses of insulation layers in walls and roofs, multi glazed windows, external shades to control the amount of sunlight entering the rooms, air conditioning using heat recovery systems and air purifiers, using LED bulbs as the most efficient lighting devices, regenerating electricity from the movements of building components such as elevators and last but not least applying strategies in order to reduce the amount of water waste in toilets are amongst those tactics which have been used commonly in the BSB’s buildings (Broad U.S.A Inc., 2010).

The average thickness of wall and roof insulation in cold countries is 10cm while in BSB's Sustainable buildings they use 35 cm of insulation. They also use quintuplet glazed windows in contrast with the regular double glazed windows.

On the other hand are the countries with a hot climate in which construction uses a maximum 3cm of thermal insulation and in most of the cases even that thin layer has not been applied. In this case the BSB has designed buildings with minimum 15cm of thermal insulation and double or triple glazed windows. By controlling only these two building elements they could provide pleasant environments inside their buildings with minimum energy consumption during summer and winter in both cold and hot countries (Broad Group-b, 2009).

The other considerable energy saving measure in these buildings is the BSB's own innovation in AC systems. The system is a combination of heat recovery from the exhaust inside air, controlled heat exchange with outside air and especially designed air exchange. It provides the freshest air currently possible at the required temperature with the least energy loss possible. This Air Conditioning system, depending on the local climate and the time of the season, is capable of recovering between 7/10 up to 9/10 of the energy. In order to understand the difference between the amount wastage of natural resources' in ordinary buildings and the BSB buildings it is useful to convert the energy used in the two categories into the amount of oil used to create that energy. The average heating, Ventilation and Air Conditioning energy consumption in conventional buildings converted to oil is a figure around 35 to 70 litres per square metre. Figures drop to 1/5 in BSB's products where the energy consumption becomes 7 to 12 litres of oil per square meters (Broad Group-c, 2012).

Health and Comfort

Based on the World Health Organization reports 68% of the transmission of human diseases are caused by polluted indoor air (World Health Organization, 2010). Although in buildings such as hospitals some standards and regulations are applied on the quality of indoor air to control contagious illnesses; yet, the importance of controlling the quality of air in residential buildings has been relatively neglected. The quality of air in all living spaces is becoming one of the main concerns especially in mega cities where air pollution caused by humans' daily activities endangers lives. One of the other main reasons of air pollution chiefly in Middle East, Africa, Australia and southern America is the 'atmospheric particulate matter' AKA 'particulates'. Controlling such phenomenon which are caused by humans' behaviour not only causes for peoples' change of mind toward environmentally friendly living to sustain the earth in long term but also calls for immediate energy efficient systems to provide healthy living spaces placed in polluted and populated areas to keep them safe. The BSB has used innovative digital system to produce purified air for their buildings users. Each room benefits from air quality control sensors which can analyze the indoor air and compare it with the outside air. This real time analysis enables the system to save energy and produce purified air as needed. Being expensive, had made the 'super filtration' systems to only been used in very specialized facilities such as computer hardware production companies. The 'Broad' company has made this technology so affordable therefore they could be used in regular housing projects. The three stage filtration takes out particles from large to small respectively. The final result is air which is purified from the 99.8% of all particles. In this case almost all of the pollution is going to be brought inside the building by people coming and going. Nevertheless the air inside the building is going to be 20 times cleaner than the air outside the building (Broad U.S.A Inc., 2010) (Broad Group-a, 2012) (Broad Group-c, 2012).

3.5.4. Prefabricated building

As it has been mentioned before, apart from all the innovations in mechanical systems being used in the BSB's buildings it is the construction which can be named as the prominent and pioneering aspect of the project as some eye-catching features have been demonstrated in the construction of this building. In fact we can regard their products as the first skyscrapers in the world that have been highly standardized. The BSB had built two other buildings before the 'T30', both in 2010 and in 'super fast' construction mode. Their first 'super fast' project was the BSB's 6-storey pavilion at the Shanghai Expo in which the assembly of components took only 24 hours (Broad Group, 2010) and their second fast build project was a fifteenstorey hotel assembled in only 6 days (CNN Travel, 2010). Until October 2012 BSB Company had built 17 structures all of which except one was built in China. They have already planned to expand the area of their work in other countries such as Russia, Brazil, Mexico and India (Hilgers, 2012).

The basis for the 'T30' project construction is modular prefabrication. The hotel consists of the main building with 17,338 square meters of area, the lobby with 264 square meters and 3039 square meters of parking spaces. The main building being the main part of the 5-star hotel has a capacity of 700 beds distributed in 316 standard rooms, 32 suites, eight ambassador suites and two presidential suites and other facilities such as swimming pool, bar restaurant gym and a helipad. The 30 storey building has been divided into 15.6 * 3.9 m modules which are known as the 'Main Board'. Each 'Main Board' comprises floor, ceiling, ventilation shafts, water pipes and drainage, electricity wiring and lighting devices, all of the structural components such as pillars and diagonal bracings and of course all the tiling and kitchen and sanitary furniture in addition to doors and windows (Broad Group-c, 2012). After being fabricated in a factory [Figure 3 .68] which is located with an hour of driving distance from the 'Broad Town' [the area where the company's headquarter, campus and many other facilities are located], modules have been transported to the construction site by tracks each capable of carrying 120 m^2 of the main board (Broad U.S.A Inc., 2010).

Figure 3 .68 The Broad company’s production line

Employees’ line-up for a morning briefing in a Broad building modules (main board) production line. Picture (Hilgers, 2012).

On the construction site labourers screw the modules together and finalize the joint seams then complete the tile work and the paint job. Interestingly about 93% of the work has been done in the factory which is amongst the highest percentages of factory made products. This volume of prefabrication leaves only 7% of the work to be done on the site. It becomes more interesting when we realize the average amount of work being done in factories in conventional prefabricated buildings is around 40% of the whole job. Contrasting with the builders that make high-rise buildings using conventional methods, the BSB, uses up to 20% less steel and between 80 to 90 percent less concrete in order to build their buildings. Not only have they saved in the materials used to form the building but also they have reduced material consumption due to the reduced waste. Compared to conventional buildings the construction waste has been reduced to less than 1% in the T30 project (Broad U.S.A Inc., 2010). Due to Broad’s statistics, a normal high rise development on average results in 3,000 tonnes of waste yet, Broad’s buildings have only 25 tonnes of wasted materials. For the technology we have at hand the BSB’s process can be regarded as optimal. It benefits from the highest level of standard and quality control possible. During the construction process there has not been any fire used on-site. No water has been used on site [conventional buildings use 5,000 tonnes of water on site] and dust production has been reduced because there was no welding, no concrete pouring and no polishing using sanding machines and more importantly, no one was injured during the construction process (Broad Group-c, 2012).

Apart from the excellence in production, assembly and waste management, this project has been introduced to the world chiefly based on its prominent cost and time management which runs through the entire cycle of production, delivery, assembly and completion. The gigantic hotel cost £17,000,000 for the BSB. It is worthy to note that the tower hotel costs 30% less to build compared to other conventional buildings as the cost for the T30 project has been $1,000 per square meter which is usually $1,400 in similar buildings. The project has been developed and delivered to the designed timeline. The ground breaking was on the second of December 2011 and after the pre-construction preparations the modules’ assembly took only 360 hours [15 days] built by 200 labours and the hotel was operational on 18th of January 2012 as was planned. Generally, the total duration of the project was 45 days from the ground breaking to delivery of the building (Hilgers, 2012). Having said all of those claimed to be positive features of these buildings it also has to be said that since the modular buildings are highly inflexible it is rare to make a large variety of internal spaces in one building. It can be seen that in order to build the lobby for the hotel they had to attach an odd shaped pyramid to the main building which doesn’t do much to help to improve the building’s aesthetics [Figure 3 .69]. The designers’ hands are tied by the constraints of the production facilities, transportation vehicles and crane carrying modules. Walking around in the tower hotel the users may find the corridors too narrow or staircases appear too industrial (Hilgers, 2012). Generally the building does not represent any development in the realm of form generation and compared to other buildings in western countries the BSB’s buildings are not the most beautiful ones. Their only advantage is that most of the other skyscrapers in china also suffer from the lack of visual qualities. Nonetheless their buildings’ outstanding selling point would be the high and uniform quality of their products. In China, where constructors use cheap materials and the level of adherence to standards are not necessarily the highest in the world, the Broad Corporation builds reliable buildings using a rapidly working system which are cheaper than conventional buildings to meet financial and population features of the Chinese society.

Figure 3 .69 T30, not an architectural gem

Poor design of the hotel and lobby link is not only clear in volumetric aspects but also detail wise. An example can be the downpipe of the lobby roof going over a window panel in the hotel building. Picture (The Skyscraper Center).

6. **Glass and cladding panels are easy and fast to install; plus they are lightweight materials which is good to be used in large scale buildings and also give a modern look to the finish.**

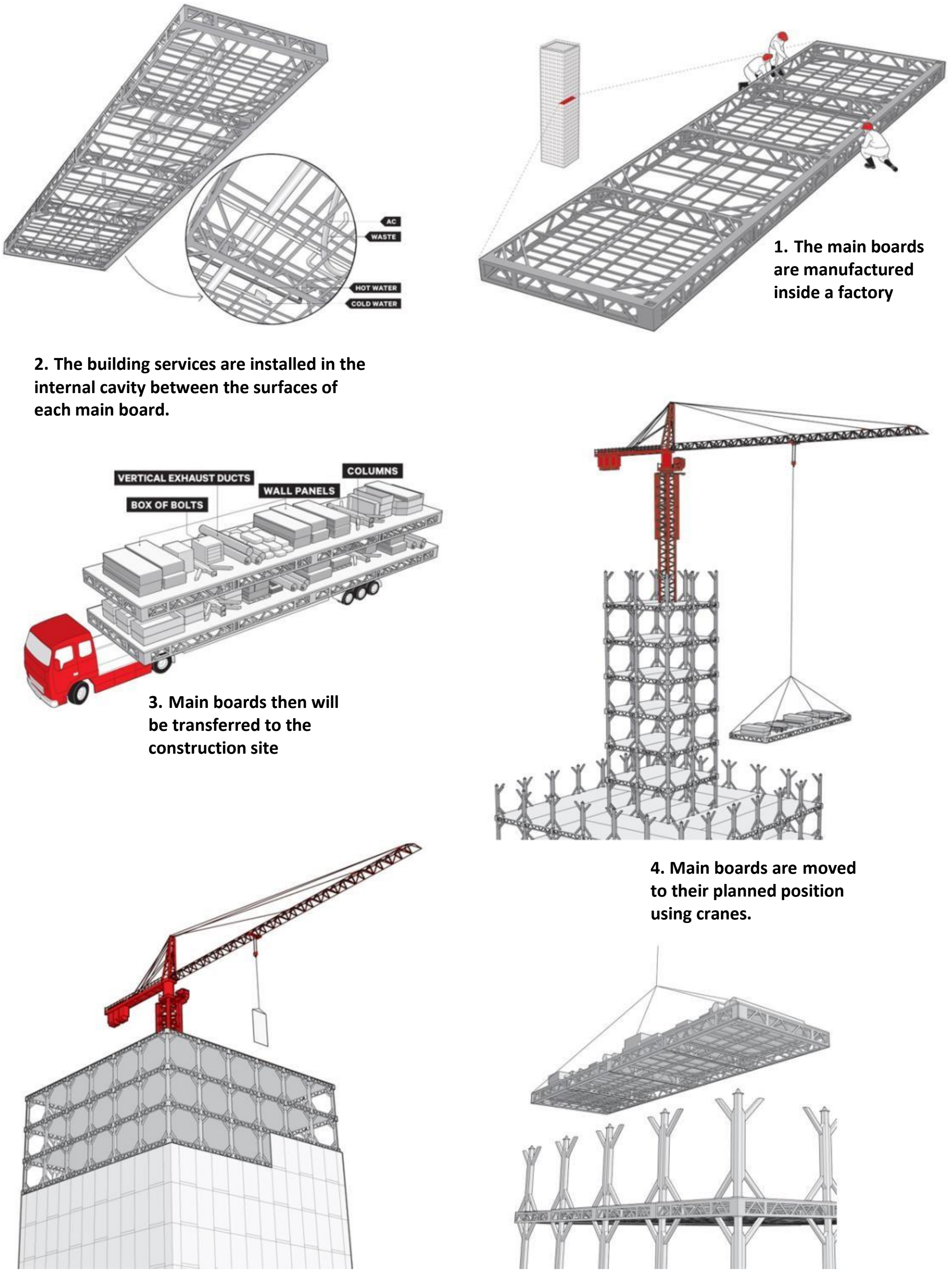


Figure 3 .70 T30’s flow of production

5. Column uniquely designed with diagonal bracing at each end and tabs that bolt into the floors above and below

Illustrations which show the hierarchical flow of key stages of the BSB’s construction process. Pictures (Hilgers, 2012).

3.5.5. The future

Every day the Broad Company works on new projects to continue on their mission to deliver new concepts to the construction world. Recently they started a new project which is called J220, a two hundred and two storey building which is going to be built mainly in factories. This tall building which is going to be known as the 'Sky City' [Figure 3 .71] is intended to replace the 'Burj Khalifa' as the tallest building of the world. The company has hired some of the engineers and designers of the 'Burj' in Dubai to work on this new project. They have already made two large scaled models of the 'Sky City' and as it has been announced by the company the architectural design had been completed before the end of the year 2012. In May 2013 they have received the project's approval from the local authorities of the Hunan state in China and based on the announced project schedule the project was planned to commence in October 2013. The first four months were supposed to be spent on fabrication of building parts in factories and it has been claimed that after the production phase it is going to take only 90 days to assemble them on-site. Based on this schedule the project was supposed to be delivered in the April 2014 (Deulgaonkar, 2013) (Yue, 2013) (Broad Group-d, 2013). Nevertheless on July 2013 the project's progress was stopped since the building proposal did not meet the most recent regulations (Rabinovitch, 2013). In return the construction company has built a new project called 'Mini Sky City' to be a part of their ambitious project [The Sky City] as an introduction to prove their capabilities to accomplish the bigger projects(Urbanist, 2015).

Nonetheless even if the BSB do not deliver the 'Sky City' project and stick to what they have done in the 'T30' project which would be producing 30 story buildings every 15 days all around the world with the budget of $1,000/sq m resisting 9 magnitude earthquakes, they still can be regarded as a revolutionary phenomenon which based on their features can potentially address many problems in troubled areas.

Figure 3 .71 The Sky city
Sky City an ambitious project of the Broad Group currently under development. Picture (Web Odysseum, 2012).

Although it has been intended to use the most accurate and up to date information and resources in this document; yet, since most of the recent digitally produced architectural projects are regarded as a part of the ongoing development of the companies' methods and tools, they may not release much details of their work. Therefore there are not many individual detailed reports available on the work of these companies and most of the available data is reliant on what companies chose to publish. In order to conduct a comprehensive analytical research on the methods and outcomes of these works there is still a gap of knowledge which has yet to be bridged by independent research which can provide access to the most accurate figures and data stemming from an analysis of these projects.

3.6. Customization, efficiency and availability: the 'Facit Homes'

3.6.1. Introduction

In the two previous sections of this chapter, two extreme cases of design and construction approaches have been discussed which can be claimed that at many points, have strategically moved in opposite directions. In fact what we see in the work of Gehry Partners, and BSB declares their different ambitions in the building design and construction business using the same type of technologies.

At the time of designing the Disney Concert Hall, Gehry was determined to establish his career as a 'Starchitect' who designs and builds unique buildings, not only in shape but also in regard to structure and who uses all the cutting edge technology to create an artistic master piece. The Pritzker prize winner prioritized the magnificence and uniqueness of the building over timescales and budget; Gehry even had to transform himself in order to become able of creating such building. He chose extreme flexibility to achieve extreme exclusivity of the products which also caused problems due to lack of previous examples as well as the extra cost and time he had to involve during the whole process.

On the other hand Zhang Yue winner of the Champions of the Earth prize has different motivation in his work. His trend of work demonstrates an interest in productivity and efficiency. His company was directed toward the production of green products which use the least energy possible and are designed to reduce waste and even be recycled. Entering the building construction business he was intent on producing products to break every possible construction records. These buildings are very cheap to build, the construction is very fast; the product and process are highly standardized which results in factory quality and form. The BSB's buildings are not planned to have a unique form but to be built all around the world, having the same form but with different technical details of windows, insulation and mechanical systems matching the local characteristics of each construction site. The Broad's strategy of high standardization and mass production of similar modules has made their products cheap and fast to build; yet has made their buildings suffering from lack of variety.

This section is dedicated to define the third and last example which shares a common ground with both examples discussed in previous parts. This system has a moderate view toward the building construction business. In such a system the practice is based on delivering both flexibility and efficiency to the project without actually sacrificing any feature to gain another. Clearly there are still boundaries and limits which define the framework; but what is aimed at here is to stretch the limits further as well as making the best out of what is currently at hand and the secret to it, is to approach the old problems in new ways. Later in this part it can be seen how this system of work has used modern machinery and strategies [which have been defined in chapter two] to widen the boundaries and bring new values which suit the demands of today's market.

In this chapter the work of a relatively young company called 'Facit Homes' is going to be demonstrated. Founded in 2007, Facit UK LTD is raised from the desire to create a new style and approach to the design and construction of buildings. A milestone in the realization of that dream happened in 2009 when Bruce Bell and Dominic McCausland joined Andrew Goodeve in the Facit Company [Figure 3 .72]. Having graduated as artists and product designers the three of them started their professional life developing CAD/CAM related projects, mostly in Architectural and associated product design. Throughout many years of working in the same industries and utilizing similar digital systems had grown mutual interests and goals in their minds which led them to gather together and try and actualize their shared ideas; basically to make changes in the areas of the construction field which the three of them thought could revolutionize the quality of the living environment, make a better connection between the buildings and their surroundings and to reintegrate the design, production and construction link as well as the customer and designer relationships (Grand Designs: Hertfordshire 2010, 2012).

Figure 3 .72 The Facit homes team
From left to right: Dominic McCausland, Andrew Goodeve and Bruce Bell in Facit Homes office. Founders discussing their design and construction methods. Picture (Facit Homes-b).

3.6.2. Why change is necessary

Firstly, as it has been mentioned in previous chapters, it has been several of centuries since the construction industry became aware of the benefits and potentials of prefabricated buildings and during this time numerous architects, engineers and factories have tried to develop new methods and to improve them to generate the ultimate method of design and construction to build cheap, efficient and aesthetically gracious buildings and at the same time keep their options open for further enhancements to match the changing lifestyle of the users and to adopt new technologies and materials through a highly flexible process. Although a few of them could resist and remain in the market for few years; nevertheless, so far almost none of those innovative systems could be counted as the ultimate answer that their creators had expected them to be as they aimed for the new methods to replace the routine traditional methods of on-site construction.

Secondly, it is already more than twenty years passed the time when computers became involved in architecture and the building industry; yet, so far what we have witnessed as the success of the CAD/CAM methods was mostly limited to predominantly large scale and expensive public projects and a few experimental and costly projects commissioned by scientific and academic institutions or rich clients who wanted to have exclusive buildings with unique qualities. In fact all of them can be seen mostly as luxury features to showcase either the financial or/and technological or/and political power of the clients. Basically the file to factory technology as we would desired them to solve the shortcoming of traditional methods, increase the quality of the resulted products and the clients' lifestyle and to also create unique buildings built as designed to suit their users requests in the best ways possible remained practically unavailable for most people. The expensive devices and processes have also made the technologies out of the reach of small scale companies.

In this climate the work of the companies such as Facit Homes can be seen as innovative by their new approaches toward the technology. Studying the underlying framework at Facit or other groups and individual with the same approach to the building industry, it is clear that the change they are making in building construction is not necessarily only brought about by changing their way of working but mostly by changing their way of thinking and planning.

In the case of the group running Facit Homes, Being product designers has led them to view their buildings as products in many ways but they still understand the difference of houses compared to other products like shoes, dishes or cars. They understand that in order to build homes and not buildings or shelters for their clients, who are mostly families, it is essential that their products have to be designed and built economically yet in a high quality and rapidly delivered as well as being discrete and fully customized for the use of a specific family.

3.6.3. The 'Hertfordshire house'

Similar to many of their famous predecessors in design and construction, being one of the first groups to try a futuristic approach in their projects required them to run tests on many aspects of construction detailing and strategies to verify the practicality and feasibility of the design. Being a young and unknown company entering the market with limited resources had made such experiments almost impossible for them. Therefore after the initial studies and planning they decided to advertise an offer for the design and construction of a house for a family to attract adventurous clients who wish to be the patrons for an almost experimental project. A couple who wanted to move to Hertfordshire to retire [Figure 3 .73] decided to take the opportunity to participate in the experiment. Since the methods which were going to be used to build the house were extremely new, the couple's house would be the first of its kind in Britain. Such an opportunity is quite tempting for anybody; but at the same time it is risky for a family that intends to spend their life savings on a prototype of a concept.

Figure 3 .73 Facit Home's first clients

Celia & Diana, a couple who took the risk to become the Facit Homes' first clients to build their home using the new technique. Picture (Facit Homes-a).

Accordingly Facit's first commercial project with a parallel agenda of finding the shortcomings of their method was started. In line with most modern practices in any industry, green production is a fundamental principle. Thus the house was designed to be environmentally friendly as far as is allowed by today's technology (Quirk, 2012). Instead of using concrete foundation, steel screw piles were drilled into the ground [Figure 3 .74] and the house benefits from the latest available ecogadgetry to control and reduce the energy consumption. Walls are airtight and after measuring the necessary thickness of insulation, in order to provide thermal comfort inside the building, the internal cavities of walls were filled by recycled newspaper insulation. The exterior walls are part rendered and part clad. Timber shades on the south side which are compatible with the building's orientation and the angle of solar rays in different days throughout the year maximise solar heating in winter and keep the house cool in summer [Figure 3 .75]. In addition recycled materials were used to build the decking in front of the house.

Figure 3 .74 The Hertfordshire house's foundation
Screw Piles. Picture (Facit Homes-c).

Figure 3 .75 The Hertfordshire house's design features
External shades are designed to allow maximum sun light inside during winters and keep the house cool throughout summers. Picture (Miller, 2013).

One of the most important features of this property is that it has been designed matching the spatial needs of the users which makes this house exclusively designed for them [Figure 3 .76]. Customization is a feature that hardly could be found in any other house being built in the price range of a normal house. It is interesting that Facit’s team delivers such qualities at about 20% lower cost on a 30% reduced program against the traditional architect, client builder model.

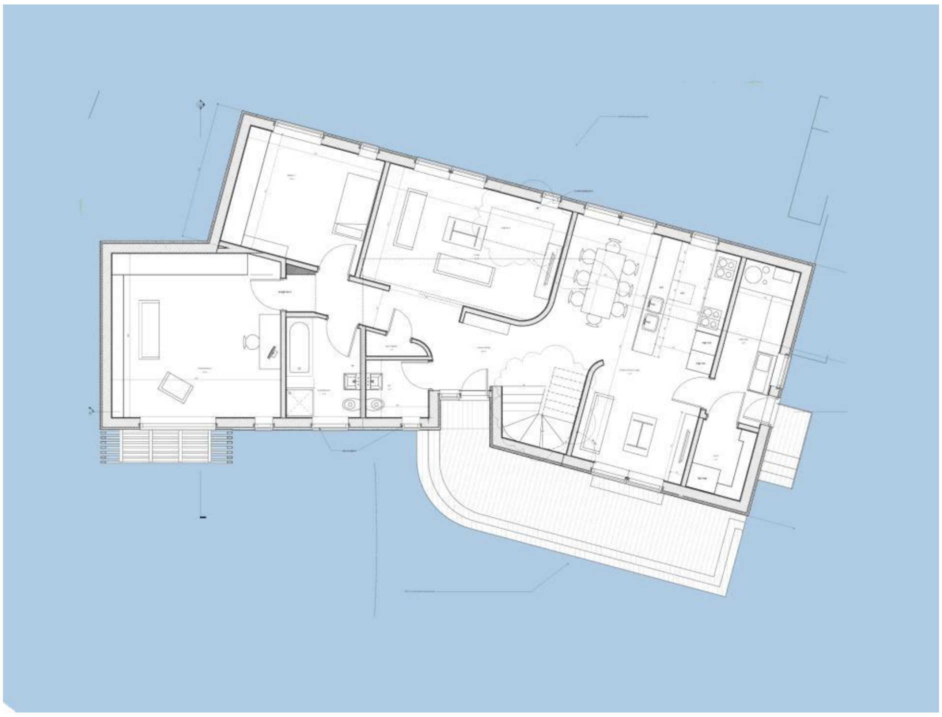


Figure 3 .76 The Hertfordshire house’s Plan

The house has been especially designed for the couple. As an example: two study rooms have been placed in the ground floor to be used by two academics who may need privacy while working at home. Picture (Facit Homes-a).

Since the project was partially experimental the Facit Company had a lot to learn from it. Being designed using computers and fabricated by computer controlled devices, designers expected the product components to be produced with almost zero tolerance. But throughout the process, the project team realized that the idealistic view of zero tolerance for the building components is not fully applicable due to the slight deformation of the components influenced by the environmental features of the construction site; or how to repair the flaws of the process which appear when other groups get involved in the project (Grand Designs: Hertfordshire 2010, 2012) (Facit Homes-a).

In order to have a better understanding of their products it is useful to investigate their flow of work, strategies and methods that they use to design and build their buildings.

3.6.4. Design

Since their method of construction is quite flexible it allows them to come up with innovative designs. As architects they consider the characteristics of every single site situation. They try to involve the clients’ ideas, requirements and lifestyle as much as possible which make their designs unique. Compared to the majority of current housing projects their design approach can even be considered as a return towards traditional methods where standardization, mass design and mass production are no longer priorities since they are no longer considered as the main elements of increasing efficiency and productivity. As has been mentioned before it is not the revolutionary design approaches that make Facit’s products innovative; but it is the creative minds and advanced technologies that make each of their houses unique even though they still use some crucial elements of traditional systems. Therefore the result can be a normal customized house or a fully modernized building depending on what the client wants. The forms of buildings are not determined by the machines setup in factories or the capacity of trucks delivering them to the site; instead each house is formed as is fitting for the project. Bruce Bell stated in their website that the “*project brief is formed by a dialogue with the client where we have to not only taken onboard their initial ideas for project but also get to the root of what it is that they are trying to achieve with it, how is it going to change their life and also what is their life like*” (Bell, 2012).

In the beginning at the conception of the projects, there is almost no sign of the digital technologies and traditional paper and a pen still seems to work the best for company’s designers [Figure 3 .77]. Being unlimited with respect to the scale and rationalized volumes expands their capabilities for innovative design and the ability to experiment with forms and spaces. In addition the hand also can provide direct link between whatever forms in designer’s mind and what appears on paper. Similar to old style architects they use art, design engineering and nature as their sources of inspiration and combination of those inspirations in a human mind can create innovative forms. The results are different from one designer to another and from one project to another. That is the distinction of the true essence of architecture and form generation. Bruce Bell defines their flow of process resembling to creation of a 'virtual 3D jigsaw puzzle'. In that system they think of each room separately as they may have different characteristics at the same time a gathering of singular spaces under the roof of the house should radiate a unified collective personality throughout the whole set. Manipulating planned spaces allows the designers to determine the best way of placing each room in the system to create a pleasant effect both in interior spaces and exterior facades.

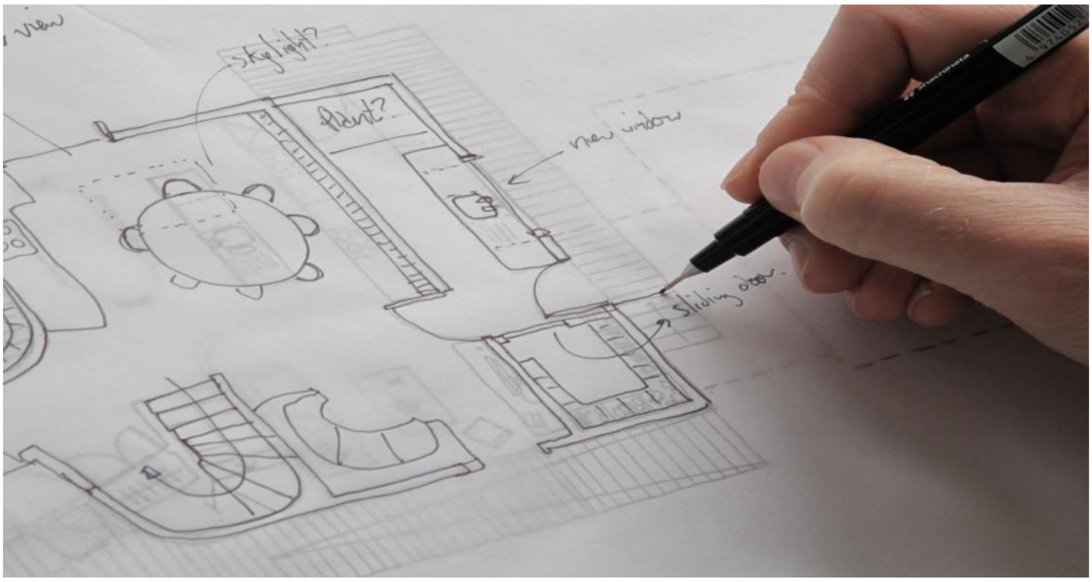


Figure 3 .77 Initial design stages at the Facit homes
Bruce Bell working on initial plans of a new house. Same as any typical design project, everything starts with old fashion hand drawings. Picture (Facit homes-d).

Despite all the building policies and the restrictions in the design and construction of modern buildings if architects design a great building with regard to comprehensive considerations in terms of space and surroundings it is hard not to get consent from the local authorities. As described by Bruce Bell, "*great architecture is not just a beautiful building, it is not just a great collection of spaces, but it is somewhere that* *you are going to have a fantastic home and you are going to enjoy it and experience it every day and it becomes a part of your everyday*”

(Bell).

3.6.5. D-Process

Once beyond the initial stages of design the next steps of the project and the direction and nature of the process in the Facit Homes is different compared to traditional systems and any other prefab housing constructors. They have patented a framework which is called the ‘D-Process’. The main concept of the D-Process is to focus on the utilization of more agile, intelligent but not necessarily more complicated methods to gain a better quality of final product; have more control over the construction process, generate more creative forms and profound meanings in the building industry and in general determine a better way of doing construction. In this system not only do the customers hire the designers of their project, but they also know that the building construction is going to be supervised and executed by the same group which means the product will match the design as closely as possible (The Self Build Guide). This way designers and clients are sure that whatever the design is, it is going to be constructed exactly as the proposal [Figure 3 .78]. In order to accomplish this and to have consistent results they use ‘File to Factory technology’ and CNC machines (Grozdanic, 2013).

Figure 3 .78 Similarity of the design and the product
Top: a render made from the digital model of the Hertfordshire house proposed design Bottom: a picture from the finished building. Pictures (Facit Homes-a).

The back bone of the D-process’s transition from design to construction is a precise 3D digital model in which every single element such as the site orientation, quantity bill of materials and even small details [e.g. the place and size of the socket plugs and light switches] are included [Figure 3 .79]. Basically each model contains several layers, each containing one or more families of data which support the feasibility of design and provide the necessary information to build it.

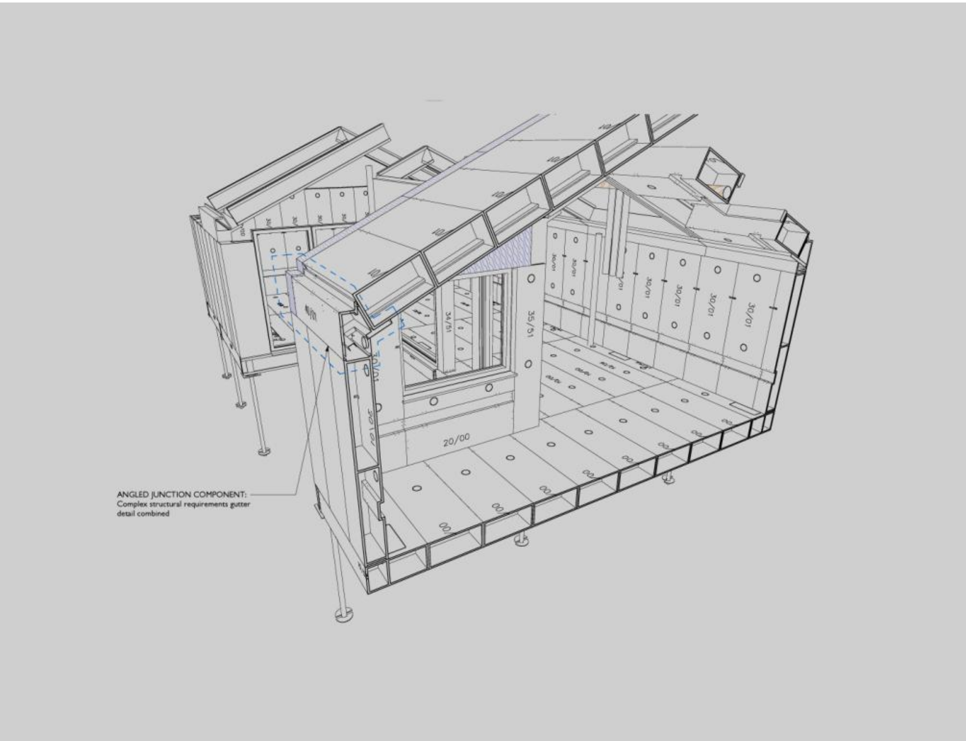


Figure 3 .79 Digital models and process
In Facit Homes the Backbone of every project is comprehensive 3D digital models which contain every individual construction details, components and their exact position. In this picture we can see that the components are even numbered which later will provide a great help for the constructors to locate them in the construction site. Picture (Facit Homes-c).

Until now all of what has been mentioned as the organization of the processes or elements of the projects could have been shared by other companies, architects, constructors, manufacturers or other methods of traditional and contemporary construction. One element that separates the Facit Home’s projects from those which have been done before all around the world are the components they use to make their buildings and the way they manufacture those components. Instead of adopting the huge complexity of the production planning, the production line setup, site delivery strategies and many other stipulations, what could be better than relocating the actual act of fabrication from the factory to the construction site? The idea here is to provide all the necessary equipment for manufacturing the building components in a portable unit which can be transported to the construction site no matter where the location [Figure 3 .80]. The machines they use for part fabrication are 3-axis CNC routers which are ideal for this type of work. There are a number of other CNC techniques applicable to the digitally fabricated home but not many that could be as appropriate for onsite fabrication (Bell, 2013).

Figure 3 .80 Onsite prefabrication
Facit Homes' portable fabrication unit is capable of cutting necessary components for making giant LEGO-shaped modules out of standard plywood sheets. Picture (Facit Homes-e, 2011).

This approach claimed to be taken for the first time in the world by the Facit Homes Company (Borgobello, 2012). The direct link between the design and the manufacturing agent provided by the computer-machine link causes the fabricated components to be the exact physical replicas of the digital model. LEGO-shaped components that can be produced being either similar to each other or different in size and shape without any changes in the production line [Figure 3 .81]. This can bring efficiency followed by lowered production costs and reduced lead time. The strategy of design and production in Facit is ‘Design For Assembly’ or DFA. The DFA is a mutual strategy shared in different product design and production industries. Production based on the DFA strategy aims for consistent quality which follows the design specifications and guaranties straightforward assembly of parts to form a component. In other words it is going to be harder for the construction workers to make a mistake. Therefore it eliminates the need for highly skilled workers and turns the process almost to a DIY project (Edwards, 2012). In such a DIY project the construction work is not labour intensive and much of the work can be undertaken by unskilled workers which could even be the clients themselves if they want to make further reduction to the costs. Although it is supposed to be a straight forward process, skill is the key to success therefore at least half of the workforce has to be comprised of skilled and experienced workers to control the process (Bell, 2013).

Figure 3 .81 Small modules in Facit products
Giant LEGO components could be carried by two persons and are made in a variety of shapes and sizes to create the designed spaces and forms. Picture (Facit Homes-f).

The way Facit uses DFA is to create the timber structure which they call the ‘Chassis’. The name is given because the so called chassis encompasses many of the separate products traditionally found into a single product. Ground floor slab, wall structure, roof structure, sarking, trusses, joist hangers, structural floors, internal studwork, firings, formed gutters, ventilated roof spaces, parapet details, etc. could be designed and manufactured in a way to be gathered in a single component in this system [Figure 3 .82]. When the quality is consistent surprises are reduced to almost zero and you know what you expect the building to be and you always get what you have expected. As clients are involved in the design as well as construction consequently they have more control over the overall project to satisfy their expectations. Describing the D-Process in Facit Homes' website, Andrew Goodeve stated that "*Our homes are built with all the efficiencies and qualities that you would expect to find on a production line; but more important maybe than that is that the client can engage with us and have unlimited design possibilities. By utilizing the D-Process we eliminate all of the uncertainty so a Facit home is built as designed*" (Goodeve, 2013).

Figure 3 .82 Service cavities
Ventilation voids and air hatches are prefabricated by the CNC machine. Circular holes are planned to match the insulation injector machine. Picture (Facit Homes-a).

Using the computer - CNC link, not only can they fabricate walls and structures of buildings but they can also produce furniture and other building components such as cladding, solar shades, kitchens, stairs but not doors and windows so far as they tend to be fairly specialized [Figure 3 .83]. Since these houses are made of large interlocking components, any house they design needs to be broken down into blocks. The process of breaking down is mostly automated and only certain parts of the building which may need special calculations or have complicated shapes are designed manually. The dimensions of the construction block are determined by parametric calculations that can be manipulated to result in the desired components best suit to every individual projects (Bell, 2013).

Figure 3 .83 Precision
Facit homes is capable of designing and fabricating some furniture with great precision, using digital modelling and CNC machines. Pictures (Facit Homes-a).

In every project, based on the preferences of the clients, site orientation, light, etc. there can be curvilinear forms in the design proposal; yet, in Facit although they have proved their capability of constructing such forms as is apparent in some of their existing buildings, they try to avoid such forms as they reduce the efficiency of the project particularly because they increase material waste.

Considering the weight resistance of the timber components used in their buildings there is a limit in the height of the blocks as well as in the number of storeys which limits them to a maximum of two floors. Nevertheless by adding for example steel members to the structure, then the height of the building and consequently the number of floors can be increased if needed [Figure 3 .84] (Bell, 2013).

From the material point of view their work is currently limited to plywood. What happened so far was to master their work using the same material and try to improve their design quality which is going to be built by that material. A great challenge for them or others who work on onsite fabrication concept is going to be the application of other materials which are local to the construction site (Goodeve, 2013).

Figure 3 .84 Further improvement of products
Steel components can be added to the buildings structure to increase the number of levels and the height of each level. Picture (Facit Homes-e, 2011).

3.6.6. Sustainable products

Reviewing their process and products, the influence of sustainability can be witnessed throughout of the design, production, lifecycle and after use of Facit Homes' as they take a longer term view on their products. They believe that sustainably is not determined by just reducing the negative environmental impacts of their products but also by reducing the operating costs of their products. At a time where energy bills are growing exponentially, reducing energy consumption not only will reduce the co_2 footprint of the building but it will also shrink the energy costs for the users. Dealing with sustainable features is mostly not easy as parameters of sustainability sometimes have an inverse influence on each other. Thus, in order to actually make the different systems of a sustainable project work together, detailed research and accurate planning have to be made. In addition to all the data gathered from the research, computer models can make a significant difference when designers are required to run tests and evaluate their products. One of the prime focuses of the Facit in their sustainable buildings is to prevent heat loss and conservation of energy. Their chief strategy to save energy which is also the most straightforward one is to build well insulated buildings which are air tight. Due to climatic features of each building site there are mechanical devices which can add to the sustainability values of their products.

More than thirty percent of the materials used in conventional construction projects end up as waste. Using shredded recycled materials as insulation means no waste is produced from the rigid insulation off cuts as well as reusing waste paper and clothes. On the other hand waste timber produced in construction operations can also be used in modern mechanical systems to create heat or electricity for the daily use of residents as they did in the Hertfordshire house(Grand Designs: Hertfordshire 2010, 2012). Dominic McCausland suggest that a revolutionary change should happen in the way of thinking and building houses as he stated that "*I think that Facit is the future of the sustainable housing; I think the traditional methods have to change. Already our basic house system is way above the legislation required and everybody has to change the way they work and we are doing that already.*"

Their ultimate goal in construction is zero waste and apparently they are very close for everything up to first fix stage. The more traditional processes [dry lining, rendering, etc.] are a bit more wasteful and they try their best to eliminate such processes. Their manufactured components are designed to be as efficient as possible, with the standard components resulting in about 3% waste. The more bespoke components have more waste but they cut the off cuts into square items on the machine and use them in the construction process for stiffening walls and alike. As it has been mentioned before the remaining waste wood is collected and burned in a Combined Heat & Power plant, thus all wastes are used somehow in other ways (McCausland, 2013).

Despite all the creativity in designing the process and using cutting edge technology to create technologically, aesthetically and functionally exceptional buildings even the initiators themselves believe that the methods has a long way to go and numerous issues need to be solved and improved through continuous research and development. The future goals of Facit Homes as described by the designer are to create better homes by constantly developing their work and to design and to bring those homes to a wider audience. They also feel the need for development of new tools for house builders/ developers to build Facit Homes on a mass scale. On the other hand he counts the obstacles as the clients' low appetite for one off homes as they are not yet popular; basically how they can send their messages to their possible clients to convince them to choose their products over the mass produced houses. It is also critical for them to change the pessimistic view of people in regard to timber structures and modern architecture. It has to be noted that convincing developers, is as critical and crucial as convincing users (Bell, 2013).

3.6.7. Mass customization

What is demonstrated in the work of Facit homes in production of these types of buildings could be regarded amongst the most recent trends in providing affordable customisation in architecture and construction. None the less this trend is not one of the first endeavours in realisation of affordable customised products known as mass customisation.

In fact mass customisation is a production method that tries to satisfy the unique expectations of customers while bringing the benefits of mass production into the equation (Tseng, 2013).

In this essence many building designers and manufacturers have tried to make unique buildings which are affordable, carry standard qualities and need less skills and resources to be built. Masa Noguchi, one of the researchers and theoreticians of this realm who has founded the ZEMCH [Zero Energy Mass Custom Homes] network defines his concept of mass customisation in building construction [mass custom design] as follows. Every building is made of different spaces and a customised building is a product of the collaboration of customers and designers to form these spaces based on customers' needs. These spaces are considered as building components (Noguchi & Hernandez, 2005). In this approach: "these housing components are mass-produced [at least, the designs of these components can be reusable], but the home itself is customised by the user's direct choices of such standard components. The exterior and interior designs include sub-categories such as the roof, walls, doors, windows, balconies, and front entrance arrangements for the exterior, as well as the kitchens, sanitary facilities, bathrooms, washrooms, toilets, storage, and finishing arrangements for the interior. In addition, the variety of sizes, materials, colours, and textures available for each component, as well as the variety of amenities offered, help expand the number of housing variations. Consequently, in order to meet clients' individual requirements, the manufacturers are able to provide a myriad of housing variations for their clients without producing a number of standard model homes that are usually designed on a speculative basis" (Noguchi, 2003). "The application of the mass custom design approach may have potential to reduce production costs by achieving the economies of scope [based on standardisation of housing components], while helping to totally customise homes in response to clients' demands for their new home. As well, the standardisation of production processes may also help reduce construction time" (Noguchi, 2010). The shape of the building modules could remain the same but different combinations of these modules can for customized to satisfy customers in creation of their unique homes (Noguchi, 2001)(Noguchi, 2004)(Noguchi & Hernandez, 2005). "These homes should be termed 'mass custom homes'". (Noguchi, 2010)

It can be witnessed that in such an approach towards mass customisation, the building modules [rooms made of one module or few modules combined to create a room] are mass produced and their overall shape remains unchanged. The customisation happens in the quality of combining these modules, interior as well as exterior finishes and some building ornaments; therefore the economy is gained through mass production of large building modules.

Technical comparison of the Noguchi approach with the Facit Home’s exhibits the clear differences. Although Noguchi’s innovative way has separated his customised buildings from mass produced houses, products such as the Facit Home’s inherit the flexibility of CAD CAM systems which allow them to be:

- customised in a higher level since the standard modules are much smaller and are designed based on the building forms
- more efficient since intelligent production methods of CAD CAM systems reduce waste, eliminate manual calculations [since the production program and calculations are executed automatically and simultaneously]
- made with less skilful workforce [therefore costs are reduced]
- Done much faster since factors such as buffering transportation and setup time have been eliminated.
- More efficient in their lifecycle because computers can evaluate and modify production and products to gain better efficiency.

In conclusion Noguchi homes and the Facit’s products work in the same direction but the use of computers in making more efficient and customised products can introduce the Facit Homes and other companies and individuals who follow similar methods as the next generation of the classic mass customised houses of Noguchi.

3.7. The Most recent trends in digital architecture

3.7.1. Introduction

The focus of this chapter is to demonstrate some of the most recent activities and products of the digital world which has been introduced to the realm of architecture. Some of the great examples of the application of digital technology have been described earlier in chapter three. The influences of the examples which are going to be defined here may not be as proven as those defined in the previous chapters, but they appear to have the potential to play an important role in the future of the building architecture.

Development of digital technology is becoming exponentially quicker. Many of the tools and techniques which are now used comfortably to design and make buildings did not exist couple of years ago. These devices and methods are gradually altering the general approach towards the quality of designing and construction. Results are soon to be seen in the daily lives of many of us and in the urban structure of our cities. Such important phenomenon needs large amount of attention and investment in research and development to keep it in the right track and on a desirable speed.
As it has been mentioned, the progress has been happening in the design and construction devices, techniques and strategies that a few of them are going to be discussed in the following document.

3.7.2. Crowdsourcing

Nowadays we hear a lot about crowdsourcing and its subsidiaries such as crowdfunding. Its strong presence in a large variety of projects may include activities ranging from gathering funds for students' education costs to gathering a group of specialist in a field to do a project and many more. In other words, it involves accessing the required thoughts, objects and materials or services provided by a vast number of people (Merriam Webster).
Although the concept has been in existence for centuries; yet the term,

'Crowdsourcing' was first used in 2005 by Howe in his paper 'The Rise of Crowdsourcing' to describe an online phenomenon (Aliki Papadopoulou & Giaoutzi, 2014). In fact the formation of this new term is due to mixture of the two words of Crowd + Outsourcing (As & Angelico, 2012).

Systematic concept of the Crowdsourcing work frame is initially based on sharing a request for services or products with the public and looking for the most suitable response from the public which could provide the best answer for the initial request. Here, the idea is that no single mind is aware of all aspects of a problem, each person may be capable of solving a part of any problem and as a result, a comprehensive answer to a problem could only be provided by combining the efforts of a group of individuals, each having a certain expertise. This method recently has been used by many different academic organizations and industries as an innovative tool for problem solving which may pave the way for more creative answers, services and products while saving time and money compared to the older conventional methods of solving problems. By the development of 'online collaborative problem solving' formation of the online platforms for such activities is witnessed. These facilities allow 'employers' to share their requests with the 'potential employees', and based on their skills, individuals can participate in projects. Amongst the most popular online 'Crowedsourced' websites which have used the information provided by the public are the Wikipedia, Waze, Arcbazar, Facebook and OSM (Aliki Papadopoulou & Giaoutzi, 2014).

Although the nature of Crowedsourced projects in many respects is against the conventional characteristics of architecture projects, yet interestingly architecture is one of the fields which are getting more and more involved with this system of work. Based on the published statistics of the IBIS world's industry report and the US census bureau, the majority of construction projects do not involve architects in the process. As an example in 2011 only 41 percent of the construction projects in the United States had used professional architectural skills. The difference between the amount of money which actually has been paid and the potential amount which could be earned by providing architectural services is unbelievably around $22 billion during the period of the same year (As & Angelico, 2012).

Alastair Parvin [the cofounder of the 'wikihouse' which runs one of the leading architectural crowdsourcing projects] in his paper points out the fact that architects do not use their full potential to serve the whole society; basically throughout the world, all of the architects dedicate their services to only the 1% of the richest. In fact the current system puts architects out of the job while depriving the majority of society from their services. This also has a negative effect to the quality of our living spaces and the appearance of our cities. He adds that in order to make a move on important issues "*such as urbanisation and climate change, we will need to develop micro, low-cost, high performance sustainable design solutions that can be copied, locally adapted and manufactured anywhere, by anyone – even those who are beyond the reach of conventional capital-led development, and the forms of debt and government welfare that fund it*" (Parvin, 2013).

Currently, the major reasons which cause the clients to avoid referring to architects for smaller-scaled projects are (As & Angelico, 2012):

- Devastating process of searching for the right person to do the job
- There is going to be higher costs involved
- Deterrent fear that after all of the risk taking, money expenditure and sufferings the result may not be as they desired

ArcBazar:

The most famous online platform which is active in the field of architectural design is ArcBazar [Figure 3 .85] which has started its activity from the July of 2011 in Cambridge MA. The basic intention of the creation of this platform is to provide new opportunities for people who cannot afford exclusive architectural services. It also supports the ambitious designers to participate in fair competitions of a variety of scales "*from a closet space to urban design problems of the developing world*", where they are not going to be judged by their physic, personality or background but only their work and the quality of their design. Fundamental elements of this platform are clients, designers and contractors. Projects are offered on a twofold basis; in the first part the design job would be put through a competition and in the second part construction project would be available through another competition amongst local contractors. Undoubtedly one of the most important fundamental elements which is the networking between all parties should always be remembered as in fact it is the key element for the success of any project in this system. 'Imdat' as the founder of Arcbazar describes the organizational concept of this online platform as follows: "*Clients post a project brief and set up their evaluation criteria, their deliverables list, a deadline, and their project prize. Designers then review the project, sign up, and submit their design concepts. After the deadline, clients rank the top three projects, and the system distributes the award money among the winners. As in traditional competitions, the platform distributes aliases, which ensures the privacy of designers. This integrated feature allows designers to remain anonymous, while at the same time it assures that the eventual ranking is merit based. During the competition process, clients and designers can communicate anonymously through a public wall on the project page*" (As & Angelico, 2012).

On the other hand Michael Crosbie criticises the Crowedsourced architectural projects as follows (Crosbie, 2014):

- "*The worst thing to happen to architecture since the Internet started,*" Dwell magazine tweeted about Arcbazar when it launched.
- *Some note that it is simply driving down fees for architecture services and devaluing design*
- *The scant amount of information provided by some clients and the inability of designers to visit the project site give others caution that the quality of some design solutions might be questionable, in violation of zoning laws and building codes, and that Arcbazar is perpetrating a possible hazard to the public good.*

- *The biggest worries among professionals seem to be the quality and the price of design. Some say designs do not relate well to their environment. Some refer it as aiding and abetting the illegal practice of architecture*".

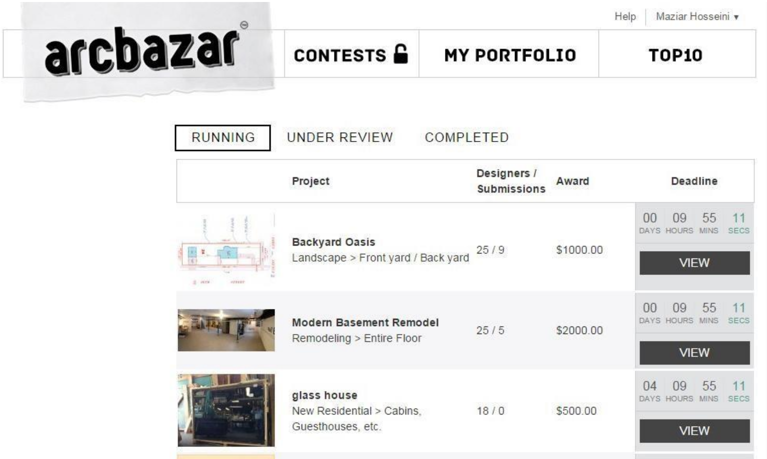


Figure 3 .85 arcbazar
'arcbazar' provides a virtual environment for architectural competitions. Project owners can exhibit their projects providing some details and competitors can participate in projects. This way it is much easier to find the right person for the job. Screen shot (arcbazar, 2015)

WikiHouse:

Open source is a term attributed to a group of services and products which are open to global access through free license (Lakhani & Hippel, 2003) (Gerber, et al., 2010). In the modern industries many believe open source paves the way for the development of products and services which also leads to a more open, transparent and sustainable production process and products (Dibona & Ockman, 1999) . The relatively new movement of free access and open source has initiated some other closely related concepts of open data, open access, open content and open standards that develop in parallel. As mentioned before, some well known cases of such involve 'Wikipedia' and 'Open Street Map' which have used users information to for example provide their services in different languages or publish real time traffic data to be accessed for free (Lin, 2014).

As it can be witnessed, today, the open source products and services are not limited only to software and also include design, building architecture, production and manufacturing similar to what can be seen in designing cars through the 'OScar' online platform [http://www.theoscarproject.org/]. In the realm of building architecture many open source projects have been introduced throughout the recent years amongst which the 'Hexayurt' project [http://hexayurt.com/] and 'Hack space' [creative, independent co-working laboratories in cities] could be named which take the 'DIY' culture to the next level.

One of the more sophisticated projects is called the 'WikiHouse'. WikiHouse provides open source designs and strategies which are accessible by anybody. Basically people can participate in the design and development projects as well as downloading and producing CNC milled buildings that do not need a high level of construction skills [Figure 3 .86] [http://www.wikihouse.cc/].

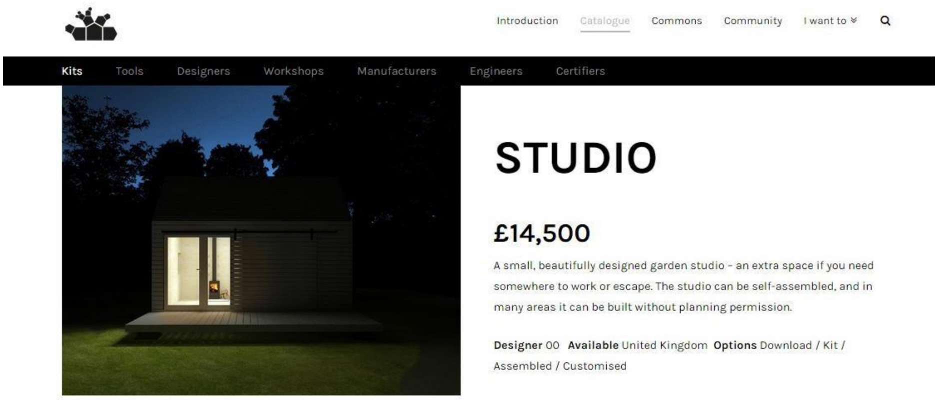


Figure 3.86 Wikihouse

On the 'WIKIHOUSE' website, people can download the files which contain CNC production data and build their own buildings. The files are free and in the demonstrated case it would cost £14,500 to build it. Their pro jects are mostly experimental. Screen shot (WIKIHOUSE-a, 2015)

Generally, most of the design and production principles are similar to what is seen in the work of the 'Facit homes' the major difference is that fact that WikiHouse is open source. In the WikiHouse website it is claimed that people can download the design data and make a new building in just 24 hours: "*It aims to make it possible for almost anyone, regardless of skill level, to freely download and build affordable housing*" (WIKIHOUSE-b, 2015).

Working as an open source architectural organization enables them to move forward in the path of democratization of architectural design and construction that was the main concept of formation of the WikiHouse in 2011 by Alastair Parvin and Nick Ierodiaconou. In their work they use open source software such as 'Google Sketchup' which is free and easy to use. Available templates on the website could be downloaded and modified by users and after cutting the pieces with a suitable CNC milling machine the user can then start assembling the pieces together quite easily [Figure 3 .87].

The first prototype of their design was built in 'Gwangju' design Binnale in 2011. As Parvin mentioned in FAB10 Conference [Barcelona 2014] although WikiHouse produces buildings and objects, but at the same time a lot of their work is dedicated to research about city economy and urban development which is going to be used in their designs. The research also includes the production of rules for making objects. These rules are intended to be the legal code of the future. These rules then can be modified to fit every neighbourhood's needs and characteristics and ultimately each neighbourhood can decide how their living spaces are going to be while linked to other neighbourhoods and ultimately the rest of the world. By having a production terminal [FABLAB] in every part of each city, each part can be self reliant and self sustained while still connected to the world.

This is the current concept of democratized architecture which has its aim in the ability to make living spaces for people who are involved in the process and not just as retail products which are made by major companies who regard buildings as capital.

Figure 3 .87 Wikihouse's digitally produced structure
The building pieces are cut using the files available on the WIKIHOUSE website and then could be easily assembled together (WikiHouse/NZ).

3.7.3. CNC machines

Undoubtedly one of the most important tools in the development of the new philosophies and concept in most of the industries including architecture are CNC machines. Basically these rapidly growing machines have opened new possibilities to actualize new forms, objects and concepts. The public access to this sort of technology is a firm step towards the development of open source production and democratization of design and production. The following section intends to define some of the most recent tools and techniques which recently have been designed and used in production procedures.

The Chinese mass printed houses:

In April 2014 a Chinese company called 'Yingchuang New Materials' used waste construction materials and cement to create an new material which could be used in their 3D printer and produced 10 buildings in a single day. The company reportedly has spent over £2 million and 12 years to develop the fabrication machine which is capable of producing self-supporting walls [Figure 3 .88]. The process includes making of structure and walls but not the roofs (dezeen magazine, 2014).

The cost of producing each building is about $5000 (ArchDaily, 2014). The recycling of waste construction materials and construction speed is quite interesting yet similar to many other Chinese projects, efficiency and productivity had been the first priority in their products. Therefore there is not much in the way of aesthetic innovations and forms have been simplified in order to increase construction speed. There's also not any innovative method used to assemble and join the components. Current products of this method are only rectangular and simple buildings with simplistic interiors and there doesn't seem to be any strategic plan to automate the plumbing, wiring and other necessary services for the building to be included to the building shell.

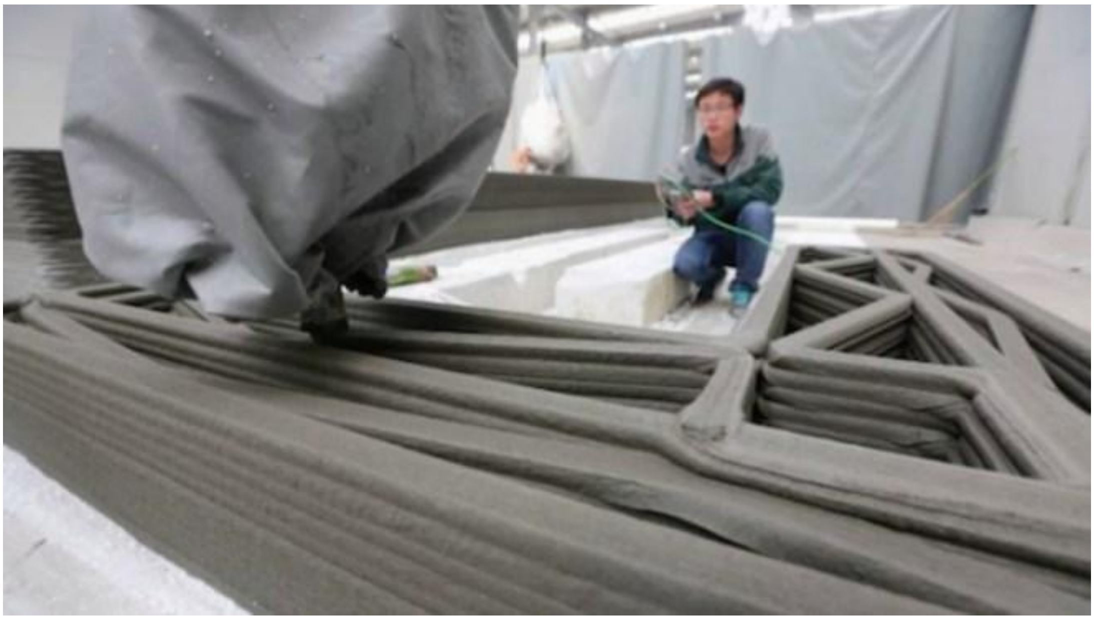


Figure 3 .88 Digitally produced concrete buildings
This machine is capable of extruding layers of special concrete on the top of each other to create selfsupporting walls. picture (Kahle, 2014)

International research centre for 3D printed Architecture in Amsterdam

As the result of the collaboration of two Dutch companies [Ultimaker and Dus Architects] the international research centre for 3D printed architecture building is scheduled to be finished by 2017 [Figure 3 .89]. The concept initially involves the making of a 3D printer which is built to a larger scale compared to the consumer grade 3D printers so as to be able to print building components. The result is the 'Kamer Maker' or room maker which is capable of printing components up to 2x2x3.5 meters in size. The main material for construction of this building is essentially plastic. The research building is going to be built in 5 storeys (ArchDaily, 2014).

Contour Crafting, an automated construction method

This new method is claimed to be invented in the search for using new tools and techniques in architecture to defeat the characteristics of conventional construction systems such as being (Khoshnevis, 2014):

- Labour-intensive & inefficient
- Slow

- Dangerous
- Wasteful and emission causing
- Corruption prone
- Costly and Always over the budget.

Figure 3.89 The Canal House
The 'Canal House' in planned to be built until 2017 in Amsterdam. A major player in this plan is a 3D printer which is capable of printing large chunks of building pieces which later will be joined together and form the whole building. Pictures (3D Print Canal House, 2012).

In this system the material [initially concrete] is deposited through a nozzle which means the building is going to be built layer by layer. In this system some strategies to provide automatic reinforcement or automatic wiring and plumbing, etc. have been innovated [Figure 3 .90]. The product can be a single detached house produced by a simpler machine or a multi storey building made by a more complicated machine consisting several types of nozzles and cranes. The anticipation is to make a regular house in less than 20 hours using this method. This system also allows the building to be designed and built using all sorts of curves therefore it could be used to execute all sorts of exotic architecture. Flexibility of this system allows it to also be used to develop lunar structures since their current project in this matter is supported by NASA (Khoshnevis, 2014).

Figure 3 .90 Contour crafting Contour cr afting uses a combination of robots and CNC machines to create a fully automated process of building construction. Picture (Gordon, 2013).

IAAC's project: small robots for making big structures

Throughout the history innovations such as arches, elevators have changed the buildings' shape and size by adding more abilities to the building construction industry. The offering of the last century to this industry has been the CADCAM and the digital technology. IAAC [Institute for Advanced Architecture of Catalonia] believes that now it is the time for robotics to make the next big change in the realm of Architecture. Unlike many other projects, the IAAC's is focusing on making robots which are capable of taking over the construction task and the robot's size does not necessarily need to be related to the size of the building. In fact they are designing and making a family of robots which each of them does a specific task in every project. These are relatively small robots making big structures [Figure 3 .91]. Each robot is connected to servos, sensors and positioning systems which allow the central operator to control the robots and their activities (Stott, 2014).

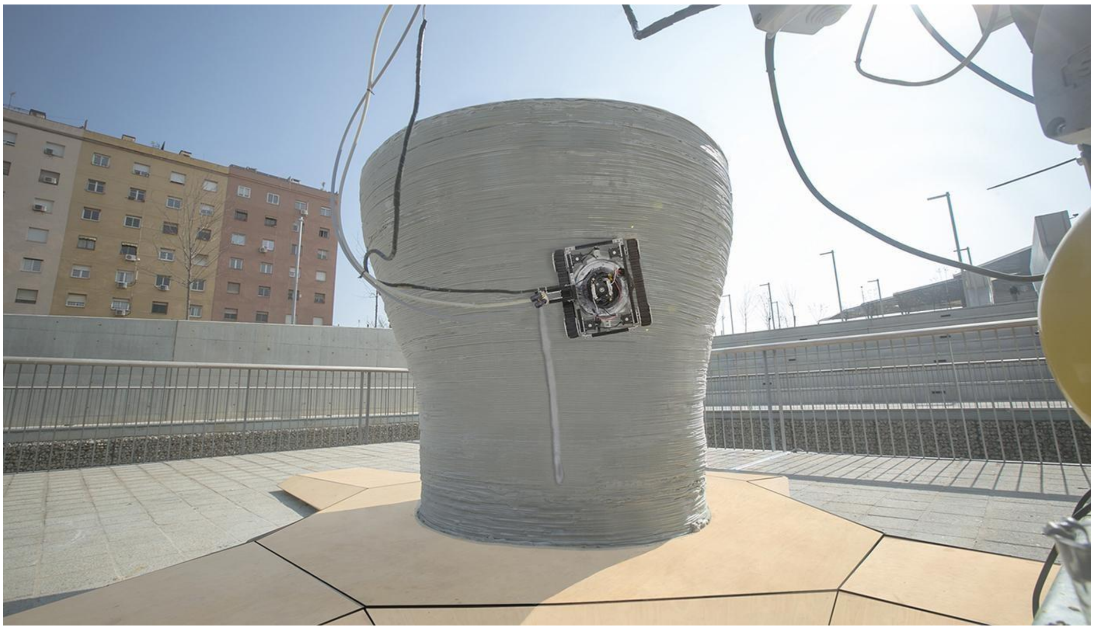


Figure 3 .91 Builder robots
In order to create big structures we do not necessarily need to use large machinery. The IAAC's concept of automated construction is to make a series of small robots which are capable of building large structures. Picture (Iaac, 2015).

By the development of digital techniques and devices, train of the digital movement in the realm of architecture is running faster and faster. Nowadays numerous universities, institutes and companies are working on the different methods and devices to facilitate the design and construction of buildings. The extent and variety of these researches and the number of people and organizations involved is so large that it is almost impossible to include all of them in just one chapter of an academic research. What is seen in this chapter is only a few of outstanding endeavours amongst thousands, and can only demonstrate a small part of those efforts being made in the current time. The growth speed is so rapid that most of the methods and devices been discussed in this chapter did not existed by the time of the initiation of this research and it is definite that no document can be up to date due to the daily introduction of the new developments.

3.8. Summary

In contrast with chapter two where the focus is to investigate production and digital design and manufacturing through a much broader overview, the exploration of knowledge in chapter three is constrained within the limits of architectural processes and products. The narrative starts with an exploration through the history of prefabrication and industrialised architecture. Section 3.2 has a general view towards the conventional and popular methods of prefabrication and the way materials traditionally have been used in those systems. In this section the traditional relationship between the type of prefabrications, efficiency and customisation has been demonstrated. Through the next part of this chapter [3.3.] it is demonstrated that how high level of standardisation and globalisation without local considerations may cause serious problems in societies, local cultures and sustainability of architectural products. In part two of chapter three, through the introduction of three examples [and not case studies], the application of modern production systems and tools in order to achieve desired creativity, required productivity and neglected customisation in the architectural products. The ambition has been to demonstrate the formation of a new working environment in the construction industry. In fact to show how digital technology can change and redefine the traditional relationship between customisation and uniqueness, efficiency and productivity as well as standardisation or the level of off-site works [e.g. in the section about the Facit homes works it is seen that by using an innovative methods including lean construction strategies they could reduce waste and costs, meanwhile still increase the uniqueness of their products, construction productivity, lifetime efficiency and recyclability. They used a structured control over the level of standardisation to define a new equation between customisation, cost, productivity and being environmentally efficient compared to traditional methods; and the most interesting factor is that they have moved most of the fabrication activities to the site by delivering a CNC machine and raw sheets of plywood. This way they saved over delivering prefabricated parts to the site and also eliminated buffering and queuing time, which are all recommended for lean construction strategies]. At last but not least, in section 3.7 futuristic movements which can define new directions to deliver excellence to architecture and digital techniques. Such researched and experiments are focused in introduction of flexible design and construction methods and devices which bring economy, uniqueness and customer satisfaction through redefining the customer-designer-contractorsupplier relationship as well as transforming the way of thinking and working environment in construction industry.

Without doubt there are numerous architectural projects all around the world which have benefited from the cutting edge digital technology and modern production techniques and strategies in order to achieve the above mentioned goals; nevertheless, each of the three examples in this document distinct from other, similar projects which have made them suitable for the purpose of this discussion.

The first example, the Disney concert hall, is chosen to be part of this research because: [further details can be found in chapter 3.4]

- It is designed and built by a celebrated architect of our time, Frank Gehry
- It is a creative design and construction project. [Even if some may disagree with Gehry and say it is not great architecture, it is still a complicated building].
- It is one of the first architectural projects which have benefited from digital design and manufacturing
- Digital technology has been highly influential on the shape of the final product and feasibility of the project. It means that computers have provided new opportunities for architects to be innovative and create new forms. In fact presence of computers had changed form of the building and the way it was built. Computers have made the project of that scale and complexity doable.
- It is interesting that the project started without computers but later, because of the complexity of the design and construction computers have been involved
- It has been influential on other architectural projects on a global scale

- In this project, digital design and manufacturing techniques have been used to take complexity and uniqueness of the building [which is a highly regarded value in architecture industry] to the next level. The Disney project is one of the projects which started a new era in the design and construction of buildings.

The second example, Broad Company's T30 project is eligible to be a part of this research, because [more details could be found in chapter 3.5]:

- Construction phase of the T30 project only took 15 days to complete
- The project is highly evaluated and tested by digital means
- The level of efficiency compared to the physical size of the project is unique in the global scale
- The project is not aesthetically pleasant and flexible but it is quite adaptable to changing environments, which means it could be built in a large variety of locations by modifying the technical specifications and still remain efficient. This means it can solve problems such as lack of buildings and spaces where these are urgently required.
- By applying digital organisation tools productivity has been raised and waste has been reduced to impressive levels [which is a requirement of the current construction industry. Some factors such as high volume production, increased lifecycle efficiency, being environmentally friendly or recyclability might have been ignored before but they are an inseparable part of today's work environment].

The third example, Facit Homes' Hertfordshire house was an essential part of this research because [more details could be found in chapter 3.6]:

- It was the first house been built in the UK using digital design and production techniques [File to Factory]
- The process is highly efficient
- The final product is highly unique and customized

- The design has creative elements
- The product is efficient
- People with limited building knowledge can be involved in the construction of such project.
- Facit Homes' projects [commercial and not solely experimental] are being built in different locations
- It redefines the client-architect relationship. In fact there a much stronger connection between the two, and clients have much more influence over the whole process and especially over the shape of their living spaces
- Since these houses are cheaper, customized and efficient it can be said that now the previously complicated digital technologies and the resulted products are now more accessible and affordable, people can have more influence on their living spaces and buildings are more environment friendly. In fact by using the digital technology, now people can have more efficient, customized buildings in a cheaper price.
- Lean production strategies [such as elimination of buffering reducing transportation time, creation of flexible production line, customised production, etc.] have been utilised in this project.

Although the example described in chapter 3.6 is one of the most recent efforts in order to make the customized built environment more available for larger number of people yet, as it is mentioned, it is not one of the first and some preceding efforts have been briefly introduced in chapter 3.6.7.

It is witnessed that the three examples share the use of digital technologies in order to achieve the true essence of each project [extreme creativity of Gehry, extreme efficiency of the Broad and more mitigated creativity and efficiency of Facit's work].

In choosing examples the objective had been to select distinct projects of different types with different ambitions which can demonstrate deeper impacts of the presence of the digital techniques in their success. The ultimate goals had been to demonstrate that 'Given recent progress in the realm of digital architecture, the potential industrialization of architecture and the greater use of machines to make buildings should not necessarily result in a higher level of undesirable standardization but might lead to a similar revolution as seen in the wider manufacturing sector'.

Through the study of these three examples it is seen that new technology has enabled us to redefine the client-architect-builder relationship for the betterment of construction projects. Therefore now architects have the chance to design based on exact clients needs or at least have better control over the construction process so the final product is matching the designs. All of these could be gained without sacrificing the economy or environmental values. This means that availability of the digital design and manufacturing techniques and machinery could be regarded as a '**sustainable**' way of progression in architecture and construction industry.

4. Conclusion

4.1. Overall conclusion

The original motivation for this research stemmed from a growing awareness of the erosion and displacement of many forms of vernacular architecture in the developing world. This has been blamed on the imposition of western values, technologies and standards over local cultures and traditions. The rational has been given that this revolution has been in the pursuit of progress and efficiency but it has obviously come at a cost to existing cultural qualities and social identities.

While the rise in sophistication in modern architectural technology is in line for some of the responsibility in this respect it might also point towards a possible solution. Today's architectural practices – as well as most aspects of modern manufacturing and construction – are now defined by the use of computing. From the earliest stages of design, through design development and procurement and even beyond site works, the computer is intrinsic to the process. It has been postulated that the ultimate consequence of the domination of computing technology will lead to a scenario where the process of design and the realisation of that design are entirely digital. This has come to be known as 'File to Factory technology'. The implication is that the architect's drawing is no longer just a representational metaphor but also becomes the means of production.

Should this scenario become reality then it has the potential to form a much closer linkage between designer and product (Architect and Building) and potentially frees the designer from the imposed tyranny of having to, for instance, specify 'standard' construction items and processes thus allowing a greater freedom to address issues of vernacular significance. It has also been interesting to note that over the course of the research the concept has broadened to not only address the influence of the advance of technology on just the designer but that there are also even more fundamental implications for all of architecture.

In order to explore the prospect of this vision approaching a reality there are three main aims defined for this research. These form the structure of the investigation and also the organisation of the written document. Consequently the main body of this thesis consists of three chapters, each covering the investigations leading to the fulfilment of at least one of the main aims of the research named in the introductory chapter.

Consequently, the first aim was to establish the context of the technology through an investigation of the state of the art in Computer Aided Design, this has been sequenced in part chronologically and in part functionally. The investigation continues through Computer Aided Manufacturing, through Process Control and the Organisation of Work within a digitally integrated production industry. The outcome is an understanding of the possible potential for improvements in workflow and product quality.

To summarise the investigations which have been presented in 'chapter two' these are as follows. The chapter starts with a brief exploration of the diversity, penetration and capabilities of CAD. Of particular note is how systems were introduced by high value, heavily capitalised industries but quickly became more widely available to the general industry sector. In parallel to the advances in the adoption of CAD it has been shown that there is also a growing advance in associated CAM technology. It was found that the capabilities of CAM are delivered through NC and the improvements of the 'Numeric Control' systems and devices as mechanical and digital devices have been described.

The next section explored the basic relationship between design process planning and production and investigated the concept of standardised paradigms and procedures which result in the evolution of standard language and concepts of the methodical design approach. As a result it can be seen that the definition of standard design models has allowed the market to identify and refine aspects of the process in the pursuit of economies and efficiency. For example, a key aspect to a design model is the system of representation – for the purpose of design development, documentation and ultimately communication. In every production process there should be a strong and mutual relationship between the design model (i.e. technical drawing) and the design and production process, where increased complexity has required the ability to move from a linear design model to a concurrent approach enabling input from a more diverse project team and noting the evolution of the accepted design models. On the other hand it has been found that complex projects require methods to expand the capabilities of the design model and its ability to contain greater amounts of data. Ultimately, it has been shown that this leads to an ability to rethink the use of a digital model in the design process and the potential for increased integration of the modelling activity within the design process.

In the next part of the chapter, the advantages of CAD applications in comparison to manual methods have been analysed. Here it can be seen how methods of manual and 2D representation fall short in their ability to carry the necessary information and are fundamentally inefficient. By explaining different levels of computer use, this document has sought to show how the design process and products have been revolutionized by the use of computers. The move starts from the transformation of CAD as purely a tool for representation towards a system which can facilitate design evaluation and other design related processes. This relies on the adoption of standards and in built tools to facilitate the creation, manipulation and storage of diverse attributes. Significantly many of the fundamental attributes to design models can be generated by software itself i.e. dimensions and similar annotations. This is one aspect of the enhancement of the design process which is also evident through the other innate abilities of software i.e. copy and paste, mirroring, rotation etc. Even the provision of guides – snapping coordinate grids etc allow for significant efficiency and economy gains.

For a long time it has been the ultimate goal for application developers to produce a modelling environment that would let the operator create a virtual version of the object complete with all physical, material and dimensional qualities. While this vision of an alternate reality is still some way off there has been progress in this direction. Operators are more proficient, machine capabilities are enhanced and the general level of associated technology is more supportive. Even the existing shortcomings of the current state of the art are not seen as fundamental obstructions and there is evidence that continued R+D will decrease reliance on physical prototypes and increase the use of computer based models. This provides an explanation of the types of model used in the design process and how they relate to the range of evaluations that provide performance data. The conclusion is that the more that the model is 'Complete' and so approaches a better approximation of reality then the greater that range of evaluations it might support and the ability to automate more evaluations [as opposed to developing other versions of the model] then the greater the benefit in efficiency and economy.

Now that the discussion has revealed that computer aided design has become ubiquitous and the development of design tools has led to the ability to construct, simulate and evaluate a representation of reality then the next challenge has been to provide tools and techniques that also provide design decision support. One possible avenue of progress is through 'Artificial Intelligence' currently a wide definition but some evidence is emerging of use in early or conceptual design stages. Equally, there are indications of the use of 'Plan Refinement' and other aspects related to 'Knowledge Based Engineering' As yet though, there is little sign of an impact from these techniques but they are indicative of the move to embody more 'intelligence' not just in the model but also in the process. This aspect is also shown in the adoption of 'Parametric Design'

Parametric design belongs to a class of operations that derive form from a set of rules and where varying the rules may produce a variety of design solutions. Instead of developing a new design model, the operator can reproduce a new solution by varying the parameter of the rule.

It has been mentioned earlier that one of the challenges for application developers and designers has been to create a cohesive model of designs which may carry real life characteristics of the proposed end products. A common use of the design model is to represent the volumetric characteristics of the object, however is has been shown that the inclusion of data describing design features will allow the testing of real life engineering features. One class of feature relates to geometry and associated functional elements. These can be defined by syntactic pattern making or rule based systems. It has also been established that feature based design is a concept that describes the ability to develop a design from components with predefined features. This can be a sequence of assembly or a sequence of operations that result in the desired form. This has attractive features but also requires that the designer has a detailed knowledge of machine operations that may be required. However there is the prospect that CAD applications with sufficient intelligence may offer the designer these capabilities.

The next section [design and manufacturing hand in hand] studied the relationship between design and manufacturing not as a set of discrete tasks but as a process. It was shown that the aim is to identify strategies which can lead to increased efficiency and economy. In fact the ultimate aim is to produce a process that makes the most appropriate and efficient use of resource. Previously the process was regarded as a series of disparate stages; however this has proved to be time consuming and inflexible. Modern thinking has identified the need to improve on this model as this would bring a number of potential benefits such as improved quality and productivity and efficiency. The pursuit of this goal has lead to new methods and management. Quality engineering applies these methods throughout all operations of a project. Computers play a central role in this systematic change. CAD and CAM are inseparable parts of a modern organisation. To this end CAPP, CAPM and CIM have evolved to support the process. The growing integration of computers which share data and support communications is the foundations of File to Factory technology. This can be seen as a logical next step given the degree of integration of computing in all aspects of design and production. Group Technology, Systems Organisation, Concurrent engineering, Design For Manufacturing and Design For Assembly are all some of the more prominent strategies being applied in modern industries to improve the whole production process. The act of process planning is the translation of design geometry, joints and features into the timeline and hierarchy of procedures, machining operations and finishing that define the artefact. There is always more than one route between design and production – the size shape and material choices all influence process planning. GENPLAN defines a systematic approach towards process planning. This system defines a method of integrating geometry, objects and components, joints and assembly into a logical production process. This information is then categorised into 'absolute knowledge' and 'constrained knowledge'.

At the end of this stage of the research it can be concluded that when the traditional manufacturing methods were predominantly classified as manual, then the quality of the product depended on the skill of the operator. Now that digital control of manufacturing is commonplace the degree of accuracy and repeatability has ensured a consistent standard of quality, similarly when process planning was essentially a human task it would inevitably contained errors and operational inefficiencies. Computer Aided Process Planning has allowed a computer to determine the optimal process and constraint checking against standards and other rules. It can also provide the link between CAD and CAM which has been identified as the key step.

Having introduced the fundamental role of computing in design, process planning and manufacturing processes it is profitable to reflect on developments in machinery and machining processes. As the technology has developed, we have seen the introduction of a wider range of supporting computer based tools i.e. automatic programming tools and cutter location data files. The technology has also been extended throughout the production line and now supports rapid prototyping and robotic controls. Numerical Control is a technique to automatically control machinery on the basis of a set of stored commands. These codes and resulting operations directly replace traditional manual methods. The technology has had the most impact on advanced manufacturing providing the ability to machine more complicated objects with operations such as the formation of compound curves. The increased complexity and capability of CNC machines has been shown to allow for more complicated operations at a greater speed and degree of accuracy. Previously data for NC machines was generated manually – with operations and tools paths being measured off drawings and manually transferred to punch tape. Now computer based applications have made this a much simpler task with automatic generations of command sequences. This has extended the capabilities of the fabrication operations and provided benefits in speed and accuracy. This has also resulted in the definition and widespread adoption of standards allowing the interchange of data between machines, companies and organisations. The introduction of 'digital part' process planning has allowed the possibility of more complicated geometries which also results in more complicated machining operations. This then results in a greater potential for conflict between tool operations which subsequently requires that the process operator must plan a hierarchical sequence of operations in order to reach the intended outcome. The development of numerical control has lead to the introduction of machines that can both manipulate the work piece and run specific operations. This functionality has now been exploited to develop a range of industrial robots that share the same lineage and can therefore demonstrate a wide range of capabilities. In areas where there is a requirement for a high degree of accuracy, repetitive tasks, hostile environments or heavy jobs then robotic operators can demonstrate significant advantages over humans. Many of the attributes discussed previously – numerical control, AI process integration, etc have enhanced the capability of robots in that their interaction and ability to respond to feedback allows them more autonomous capabilities.

The next section addressed different aspects of manufacturing planning by initially investigating discrete manufacturing and the contrast with continuous manufacturing and ultimately the effect of industries organisational changes to meet the challenges of customized, customer driven manufacturing. In essence the manufacturing process is all about an understanding of the customers' desires and the ability to convert data into objects. A manufacturing process must be organised into component fabrication followed by processes of sub assembly and final assembly. Planning this process is crucially integrated with time, cost and availability of raw materials. In a time of shortages mass production found favour as a route to market where the customer had little influence on the product. Increasingly the customer is more demanding and is exercising greater choice so a customised manufacturing process is better able to respond to a changing market. This has meant that manufacturers and customers have had to develop a tighter means of communication with integrated feedback loops. To the extent that in some instances the customer can now specify specific features of a product. In the move towards an order oriented design system the ability to fulfil the customers' wishes in a timely manner dictates success or failure. Despite good feedback loops to the customer, the manufacturer is still limited by the availability of raw material and components. This had led to the formation of extended enterprises that collaborate towards shared interests.

The pursuit of ever greater production goals has led to the concept of 'just in time' engineering. This system seeks to provide the right item of the right quality at the right place and the right time. This concept considers the totality of the project and although hard to deliver may be optimised to produce the greatest return. Basically the ruling factors in JIT systems are feedback from users, holistic production environments, flexible manufacturing processes and modularity, speed of respond to change and supply chain management. In order to satisfy market demand it is desirable to keep the diversity of products high while keeping process operations low. Technology progression is what is facilitating a move in this direction. For example a fabrication device that can perform multiple operations on different artefacts with negligible set up time.

Starting from the very beginning of CAD CAM technology and defining the offerings of the relatively new technology in order to revolutionize the traditional methods, now it can be a good time to have a look at the most recent trends in CAD CAM. The impacts of all aspects of the digital technologies on manufacturing have been compared to the industrial revolution of the previous centuries. Digital technologies are pervading all aspects of society and this impact is augmented by the ability of disparate technologies to communicate and reinforce each other e.g. autonomous vehicles. As manufacturing and fabrication became more complex there are more teams working on a greater variety of aspects of the project. This calls for closer collaboration and better communications. Consequently we can see the introduction of 'Product Data Management' [PDM] applications capable of organising all the different datasets required by the process. This impacts data exchange and management. There are also other modern means for facilitating the collaborative work of experts in different teams. The virtual environment of the Internet has provided a well established platform for initialization of the virtual teams. Through this virtual world people may gather by different means of crowdsourcing such as fund raising or finding colleagues which may not work with you in a same physical location, or even finding contractors to accomplish your projects [e.g. web sites such as Arcbazar].

Green production and sustainable products are also proven to be one of the main concerns of the societies. Growing population, limited resources and environmental issues also call for flexible, efficient and productive production lines which can reduce waste and products that use less of natural resources and produce less waste. Modern technologies can help this by accurate planning and precise testing using thorough digital models.

At the last part of the second chapter we have seen how a thorough model of products may appear in architectural and building construction projects. The term 'Building Information Modelling' or 'BIM' is referring to a relatively new system of design and documentation of design and construction data. In fact this system can connect all of the differing groupings of data and people who work within a project. This digital model applies software to conduct the flow of work and information. Similar to many other industries ambitious designers and demanding customers have made buildings and construction procedures extremely complicated over the last century. Many additional layers of data added to buildings have made designing and data access much harder than what traditionally used to be. There are also some levels of information which could not possibly be produced and accessed using older methods. A BIM model is a centralised data repository feeding all groups and being fed by all groups involved in a project. Such a model can also facilitate concurrent development of projects since different teams can update the model regularly, therefore all teams are aware of the changes immediately and can adopt a new direction or notify others of errors before it is too late. Such a model calls for a systematic change which requires every team to know and be working in a new environment. The immediate signs of improvement can be seen in facilitated documentation. Real time simulation assists the realization of design, problem solving and constant improvement of the product. Better communication and decision making during the design and construction phases are crucial benefits of such a system, the lifecycle maintenance and end of life of the project have also been planned and anticipated and could be referred to. In the end we have to remember that the ultimate productivity and efficiency traditionally come with ultimate standardization which may limit the creativity of designers, customization and uniqueness of products. Therefore there has to be a cautious consideration in the level of standardization we want to involve in every project.

Further on, the third chapter is dedicated to ‘a study of industrialized architecture and an investigation of the role of CAD and CAM in its progress’. Similar to chapter two, here the investigation starts with a reprise of the history; this time the history of industrialized architecture and prefabrication. After discussing CAD CAM technology the focus turned more onto Architecture which is the main topic of this research. Buildings as a result of using computer integrated technologies (CAD CAM) will be commonly known as prefabricated buildings regardless of how the materials or techniques have been used to build them. Here we start from the time when the necessity of making prefabricated buildings was realized but there was no sign of computers and all the work had to be done manually. This way we can see how things used to be done and how the presence of computers has revolutionized the process. The history of prefabricated buildings is assumed to date back to the early 17th century when it was initiated in Britain. The practice came about due to Britain's global colonization which dictated the physical presence of the Empire in remote areas of Australia and Africa. Lack of decent shelters and the necessary infrastructure to make them caused the buildings to be made in Britain and shipped over to where they were needed. As time passed and with the arrival of further industrial innovations, those simple shelters have advanced in quality and standards and became transformed into complete buildings whose components could be erected in remote areas.

Similar to timber structures prefabricated steel structures were also initiated in Britain to improve construction products. Buildings could be taller and internal spaces could have wider spans. Cast iron also became popular in making structures such as bridges. The first cast iron bridge [1781] was located in Shropshire. It was mainly built using precast iron parts. One of the greatest examples of using prefabricated steel building components was Crystal Palace which exhibited the application of the cutting edge techniques of that time.

Prefabricated buildings and structures became recognised for their utilitarian qualities and their applicability to improvisation. After the Second World War prefabrication appeared to be one of the most effective [if not the only] method of construction to cope with the shortage of buildings of all types. The revolution of the production process, parts and products by Henry Ford established Fordism which has transformed production industries. The result was a high level of productivity, efficiency, low waste and limited variety of products. In a time of need such a strategy could be vital; yet, we have to consider that in fact by reducing the variety and customers' choice some values are sacrificed in this system.

As it can be witnessed in chapter 3.1, there have been many different methods of prefabrication and also many different types of materials being used throughout its history. It is also mentioned that due to the fact that buildings, produced using the majority of those techniques and materials have since disappeared soon after their existence. Unattractive forms and poor aesthetics, insufficient comfort and or lack of financial and strategic justification were some of the main reasons behind those failures.

There have been a large variety of materials used to make prefabricated buildings. They were not limited to steel and timber and many other materials such as aluminium, concrete corrugated sheet and sandwich panels made of a large variety of materials such as foam, metal and wood were used. What can be seen in chapter 3.2 [prefabrication strategies] is that, several types of strategic approaches in the application of those materials exist which allow us to gain efficiency, productivity, desired functions and possibly uniqueness.

In this chapter it has been seen that there are three major approaches in off-site fabrication; component based, panel based and modular. Commonly, the component based is the least efficient but there is it is possible to create a larger variety of products; yet, on the other hand, modular is the most efficient but with less possible variety of products. Panel based is in between the two regarding efficiency and uniqueness of products.

While, more or less, all of the different prefabrication approaches have been used in the creation of a large variety of buildings throughout recent history, the popularity of modular construction is a result of the post war crisis when buildings were in demand in the shortest time frame. This came about due to the features of the modular systems which make projects more efficient and productive.

Depending on the expected result different strategies could be applied to prefabrication. As an example, if efficiency and productivity is desired nowadays it is possible to perform perfect planning and extreme standardization of the process and the products and in some cases only 5% of the construction work needs to be done onsite.

Extreme efficiency and productivity also known as mass production became popular at a time of desperate need for buildings. Mass destruction of cities needed reconstruction in terms of urban infrastructures as well as mass housing for homeless families. Countries did not have the time and money to make customized buildings in the mid 20^{th} century. But as conditions have changed by the end of the past century there were new demands from the market; there were also new technologies enabling architects and constructors to emphasize on new concepts and values in their buildings and urban spaces. The CADCAM technologies have facilitated the creation of a new level of imagination and realization in creation of spaces.

The focus within the section 3.3 is not solely on architecture itself but also the cultural and environmental influences of architecture.

The majority of the focus in chapter 3.3 is directed towards a discussion of the impacts of globalization and standardization in building and architecture. In order to demonstrate the consequences, an example has been introduced. The vast cultural and geographical diversity in different regions of Iran, its historical background and the current situation has nominated the country as a suitable candidate for the purpose of this research.

The first part starts with a review of history which demonstrates the roots of the changes which formed the modernization of architecture, urban structures and living spaces of Iran in the mid 20th century. War had changed the west and these changes became injected to the traditional society of Iran due to the fact that at the time the country had been directly influenced by the western countries politically, technologically and culturally; yet most of the time the changes and the consequent products did not match the local cultural and geographical grounds. The gap between the users' expectations and products' features had created such a degree of chaos in the urban structures and living spaces so that its aftermaths still causes major challenges for both government and members of public.

Similar to any other local architecture, in Iran there are embodied values in the materials and physical features used in buildings which have been evolved throughout history. These values match the needs of users and their daily habits as well as the local environment. Studying the two regions of Iran shows how people and the environment are different which resulted in two radically different building types. It can also be seen how a variety of strategies were developed to tackle the harsh local climatic and geographical character. Due to the domination of the west in all aspects of peoples' lives the form of the cities and buildings has changed and those local strategies are replaced by electrical and mechanical systems which use energy to provide comfort for the buildings' residents. Standardization of form which provides high productivity in building construction has become the main trend in this domain. The result is repetition of similar buildings all around the country which not only are not sustainable but also cause undesirable social and cultural consequences.

In the part two of the chapter three, computer integrated production of buildings in a variety of approaches have been demonstrated. In 3.4, 3.5 and 3.6 it is seen how digital techniques are used to respectively achieve 'extreme creativity', 'efficiency and productivity' and 'customization and availability' in building construction.

Without a doubt, Frank Gehry's use of digital technology in architecture has caused deep changes in approaches towards the design and making buildings. In fact his work had a major impact over the technical aspects of projects as well as cultural features of the work spaces in the building industry and also influenced the surrounding environment of his projects culturally. He is one of the architects who realized that in order to create unconventional forms and spaces, we have to use unconventional tools; in his case digital techniques.

The Disney concert hall has defined a new path in Gehry's career as an architect. In most cases there was no previous example of what he intended to do; thus, basically he had to initiate methods and techniques. Since he was experimenting with new methods and materials for the first time there was no guaranteed success for his work. Therefore in some cases he could not finish the project on time and on the budget. It can also be said that the end result could be different and not as good if done on the budget and on time!

Even now only a few years after the completion of some of his projects it can be claimed that many things could be done differently and in better ways but reviewing his work reveals that he was always focused on trying new things and these caused him to be ahead of his time when he was involved in every individual building.

As we see in chapter 3.4, Gehry's approach in designing the concert hall was much more sophisticated than the conventional architecture of the time and since a common compatible computing platform for him did not exist, the project had faced numerous problems and failures during the early years.

It took him some time and a few projects around the world to make the concert hall project feasible. He started the design without computer assistance and ended up with a complicated conceptual form which could not be finalized, calculated and tested without a digital application. By finishing the design he had a complex form which could not be made without using computer controlled machines. And in order to create a building which would match the original design he had to create a direct link between the software he used to design the buildings and its components and the systems which would fabricate the building parts.

Eventually the project was finished, the result was unique and praised by a large majority of people, yet this uniqueness came with costs. The project fell years behind the schedule and millions over the budget. Not many peoples, companies or cities could afford this level of financial burden; therefore we do not see many of these buildings around. It might be a perfect building in many aspects but in order to make such a product, it required a high level of expertise, highly experienced workers, and sophisticated equipment.

It should be said that the Disney Concert Hall has its own place in the architecture world, a special building to act as a tribute for a special person such as Walt Disney; A product of an intelligent mind to fulfil the ultimate need for extreme creativity and uniqueness in building construction.

In chapter 3.5 a Chinese approach has been discussed. The Chinese are famous for being extremely efficient. It could be the high population of the country which makes it necessary to use the available resources in the most efficient way. Such a population creates a huge market, demanding all sorts of products in large numbers. Buildings are not an exception. In addition the seismic features of the country make the building construction industry even more challenging. Energy consumption, air pollution and economic pressures in addition to the shortage of space, call for more modern and clever solutions to satisfy the needs of the Chinese society.

In this climate, companies such as the 'Broad Company have chosen to use digital techniques, not only to design, calculate, evaluate, plan, manufacture and construct the buildings, but also to use computers to control the buildings' energy consumption and lifecycle as well as providing the necessary information for the end of life and recycling. Such an advanced system of data management and control could be regarded as a superior BIM model.

As it has been mentioned in chapter 3.5, the Broad Company has made some huge buildings in just a matter of days and apart from that, during the construction process the waste of materials and resources such as water have been reduced dramatically. Finished products use less energy and create less pollution and provide more comfortable living spaces for their residents compared to other conventional buildings.

Nonetheless all of the efficiency is accompanied by some problems. These buildings are highly standardized. In fact they are designed to serve the standard needs and not every individual's needs. Not only is making these buildings cheap but it can be said that they also look cheap although the built quality is standard. In these buildings we see a technological phenomenon but not an architectural masterpiece. Aesthetic values have been sacrificed in order to gain high productivity and efficiency. The Broad Company is planning to make these buildings all around the world. Without a doubt, in order to keep the prices low they have to create the production units close to the construction sites, or otherwise the shipping costs and constrains would be imposed on the project budget. The workforce also needs to be highly experienced and adapted to the unique system of the work in the company.

Similar to Gehry and partners, the Broad Company also has its own case in the use of digital technology to make buildings. The Broad Company's products could be regarded as an example of the Chinese approach towards production. Cheap, efficient and mass produced. It may not satisfy the desire for uniqueness and beauty in architecture but such an approach certainly is vital in the time of need for making safe buildings in a short period of time and at a low price.

In chapter 3.4 and 3.5 we have seen two radically different projects which have been benefited from the digital technology to determine ambitions of their creators. Gehry [in contrast with Broad] has prioritized the magnificence and uniqueness of the building over the timescale and budget.
In chapter 3.6 an approach has been discussed which [compared to the two previous ones] is based on a more modern technological, systematic and philosophical view towards architecture and building construction that is recently frequently referred to as democratization of architecture. The company known as 'Facit Homes', is one of the pioneering companies in this area. The idea is to use the most recent digital technology to create customized buildings matching every individual client's needs and suiting local features and context. The product is claimed to be cheaper to build compared to other conventional buildings and may also be cheaper to run. Advanced technologies control the building to provide the most comfort for the residents and create the least waste all at minimal cost. As was is discussed in the chapter 3.6, this

shows that designers now can be closer to the construction phase and have more control over the entire process. Clients can also be more involved in the design and production process.

It seems that the building industry and architecture are both following the same route as many other industries and nowadays the advanced and expensive technologies of a few years ago are becoming more widely available for everyone. Using complicated technology, the operation of which once required highly skilled technicians and engineers, can now be accessed through friendly user interfaces making it possible for a less skilled workforce and now even the most advanced technologies do not necessarily require highly trained users. Although it is not possible to predict the future but it would appear that such a revolutionary philosophy which is backed by technology that is growing dramatically everyday could radically reform common views of building and architecture perhaps heralding a time when everybody could have the opportunity to form their living spaces.

Elements such as the availability of technology, the internet, and innovation of cheap and versatile production devices have made products more customizable and more available. In product design it is desirable to make products which follow the same quality criteria but do not necessarily have the same shape and size and ultimately have the ability to be customized to the user's required features [mass customization].

Projects such as Facit's Hertfordshire house share the passion for form generation and uniqueness of space with designers like Gehry and the consideration of efficiency and productivity have parallels to the ethos of the Broad Company; yet, apart from those features, in Facit Homes, they have also additionally democratized the process. This is what makes them and others with this view, distinct from the other designers and manufacturers, even those using the most advanced machinery and software. Steering the correct path could help them to be a bridge connecting these current themes to the future of architecture.

Nevertheless, despite all the improvements, this is not yet the perfect system. Most of the production devices have only just become available and still need to pass a long course of research and development to be able to become a part of a mainstream, reliable production line. Researchers are currently working on new devices and new materials which possibly can ease the process, making it cheaper and cleaner and facilitating a broadening of the variety of forms and sizes which could be processed at an industrial scale.

As discussed in section 3.7, the investigation of this thesis continues to discover the potential for improvements in the realm of architecture by highlighting some of the most recent technical and technological innovations.

At the moment society does not look at buildings as shelters which can fulfil their basic needs but spaces which are designed and built to match all of their requirements and expectations. Nowadays it can be argued that buildings should be built in the cheapest way while providing the highest living quality for their users and also meet 'green building' criteria. It is no more desirable for people to use their personalized iPod which can be fabricated in millions of varieties but live in places which are the exact replicas of millions of other spaces. In fact it should be said that it has never been desirable, but limited facilities and resources had made it impossible for them to have their living spaces personalized for their unique needs. As it has been mentioned in previous chapters, now flexible machinery, production lines and designs allow us to reduce cost and construction time. Flexible production equates to a larger variety of products and more possibilities for customization. Apart from the machinery, links between people are playing a key role in improvement of the design and eventually the quality of the built environment and urban structures. In chapter 3.7 some of the new tools, activities and products of the digital world which recently have been brought to the realm of architecture are introduced. Most of these new methods and tools are based on other modern innovations and services which did not exist some decades ago; Crowdsourcing is not an exception. The Internet and the extent of networks have strongly influenced industries, services and products. As seen in chapter 2.10 one of the most important influences of the internet and digital networks is the ease of communication and linking people and digital applications together. The system or activity defined as Crowdsourcing brings people in need of services closer to the people and organizations that provide services. This environment is an important component of democratization of the products and services. For architects it is one step closer to being able to offer their service to the majority of people and not just the richest 1% of the society. This means more jobs for architects and more customization for people. Global standardization and local solutions could be another product of this type of networking. An example is the work of 'wiki house' in creating a system to define global standards, offering similar comfort for all of the people through products which are modified to match their personal preferences and local environment.

It can be seen that apart from the systematic improvements, new tools also have made changes in product and production features. A large variety of CNC machines which use a wide spectrum of materials from different families have made the building construction much more efficient and created flexile production lines which lead to a larger variety of products.

Progress in the realm of the information technologies and computing has undeniably now changed almost all aspects of both industry and society, although within the domain of the built environment most people might still tend to categorise these developments as being primarily manifest in the tasks of drafting, rendering and office management. However, the evidence presented here would suggest that the likely impact is much more pervasive and far reaching that this. It can be argued that the greatest influence has come about as a consequence of the dissemination of computing down through the manufacturing sectors. The transformation in this sector has been quite remarkable and the integration of computing in design, process control and manufacturing is now ubiquitous. This has led to an ability to pursue (and deliver) an increase in the diversification and sophistication of production management, process control and product engineering which has in turn led to greater economies and efficiencies in manufacturing. While Architecture might not be able to leverage as much from these developments as, say, the automobile or aerospace industry, due to the lack of a comparable mass market for products, it is still possible to highlight undeniable benefits from these advances. These advances can be seen to deliver tangible results through a closer alliance between design and manufacturing, facilitated by computing, as evidenced through the cited case studies. It is enough to exemplify the links between Gehry and Creativity, the Broad Company and Efficiency and Facit Homes and Innovation.

Undoubtedly the rate of change will continue to accelerate and while Architecture might not be at the centre of the revolution there is enough evidence to suggest that these changes are capable of supporting the innovation and creativity required to address the needs of an evolving society. Clearly, the Architecture industry is at the junction of the traditional and a new technologically charged modern way of working.

The ultimate conclusion is that there is more to come and that these changes will come faster, be more radical and have the potential to deliver even greater benefits for Architecture.

4.2. Research challenges

As in every research, there have been a number of constraints which have influenced the shape of this document both in terms of content and in the way it is presented.

The targeted realm includes a large number of different fields of knowledge which need to work in synergy to develop the concept of digital design and construction. The ultimate realisation of this proposal would surely need highly skilled people from IT and programming, material science, architecture, structural engineering, industrial design, project management, process design, mechanical engineering, etc. This calls for appropriate investment and organization from governments and scientific institutes. Due to this fact, the research presented here has been mostly focused on investigating some of the potentials and possibilities offered by this vision of digital technology and has not dwelt much on the fundamental technicalities of the work.

The presence of digital technology in building construction is a relatively new phenomenon in architecture; therefore most of the techniques or the resulting consequences are not yet fully assessed and proven. In most of the related topics there are pros and cons but as each day passes there are new discoveries and new areas of innovation such that the accepted wisdom may be changed or even proven wrong. In many cases, some parts of this document had to be changed because of the rate of technological development throughout the duration of this research. In this type of topic, even more than others, time not only forms the scope of research but may also dramatically change the contents and results of it. In addition, digital architecture is one of the more interesting areas of development today and the growing number of people working to enhance this field means more and faster changes.

Although there are numerous people all around the world who are using and developing digital techniques, the daily rate of innovation, discoveries and controversies has made it hard to find reliable and up to date resources for this research. As has been mentioned earlier, even if an up to date source of information could be found, many techniques and data are not deterministic and could be evolving on a daily basis.

There is a global competition in the development of digitally designed and built buildings; since most of the techniques, materials and machines currently being used in this field are being continually improved, companies and individuals involved in this field have to keep a large proportion of their works secrets. This makes it much harder to find and study case studies which would help inform and illustrate the research.

4.3. Contributions

- Given recent progress in the realm of digital architecture, the potential industrialization of architecture and the greater use of machines to make buildings do not necessarily result in a higher level of undesirable standardization but might lead to a similar revolution as seen in the wider manufacturing sector.
- Being able to increase efficiency, productivity, customisation, recyclability, quality and reduce waste and also to improve project economy, digital architecture and File To Factory technology have the potential to progress as a sustainable method of production to make sustainable products.

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  Although architects mostly emphasize the artistic and architectural values of their work, the research presented here begins with considering buildings as the results of a production processes, a view much closer to the field of product design. This gives us an opportunity to step back and have a broader view towards architecture and the built environment. Strategies, materials, machines and methods which have been used by other industries could also be modified and used in architecture to result in more effective production process and better products.
- The new possibilities in creating a comprehensive product model which are translated as BIM models in architecture also have been discussed. Prevalent use of such models which can automatically control drafting, communication, access, calculation, evaluation, creation of bills of material and even manufacturing processes is imminent.
- Focusing more on architecture, it can be seen how the industrialisation of architecture has gradually evolved throughout the history and how it has been revolutionized by the presence of digital technologies.
- Different intentions in using computers in architecture which have resulted in different types of products have been studied through discussing only a few examples presenting leading projects from around the world.
- The need for making architectural products available both for the benefit of people, society and architects has been addressed and we have seen how new technology can help by providing a platform to redefine the architectclient relationship
- The need for moving towards green products and how digital methods may facilitate that movement has been discussed. This change of attitude in design and production is essential for the future.

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- The importance of mass customization has been determined. This approach can guarantee that architects can deliver buildings which can match almost all the users' needs and it is made possible with the help of digital techniques, now more than ever.

  It has been discussed that currently there is a need for global standards which can reduce waste, cost, time, etc. and result in improved built quality, comfort, efficiency, productivity supply chain management and the delivery of green features in the built environment. Besides there is a need for local modifications to these standards in order to advance sustainability of our living spaces.

4.4. Future research

Due to the constraints which formed the scope of this research it was not possible to include all the related topics which would have been useful in this subject. Some of them are as follows:

- Generation of the global and local standards. what should be included in them to maximize the benefits of such a work frame and evaluation system
- Research addressing the necessary changes in the Iranian construction policies in order to enforce regulations that rule the construction industry in Iran to design and construct buildings which are more suitable for the local context of different regions of the country.
- To discover impacts or problems of the use of CAD CAM within the construction industry of Iran.
- Development of BIM models. How can we improve the current BIM models in order to be capable of taking the role of a data storage and distribution tool which can organize the design and manufacturing of building parts?
- CNC machines, specifically designed for making buildings. What would be the best strategy in making buildings with these machines?

- On what level we can rely on automated data processing of building models to not restrict the creativity of the designer?
- What kind of new materials could be used to make the most out of the newly developing digitally integrated construction process?
  What are the advances and deficiencies of different materials being used in various digital manufacturing techniques or in regard to the size and shape of final products.
- What changes should be made in the education system of architect to make them ready to adopt the new digital methods?
- Cultural impacts of the digital design and manufacturing systems over the construction industry.
- How can we make mass customization more efficient and affordable?
- There is a need for a substantial amount of research and development in order to enhance the direct design – manufacturing link.

References

Glossary

2D	Two-Dimensional
3D	Three-Dimensional
AC	Air Conditioning
ADAM	Automated Drafting and Machining
AI	Artificial Intelligence
AMD	Avions Marcel Dassault
ATO	Assemble To Order
BIM	Building Information Modelling
BOM	Bill Of Material
BPR	Business Process Reengineering
BSB	Broad Sustainable Buildings
BT	British Telecom
CAD	Computer-Aided Design
CAM	Computer-Aided Manufacturing
CAPM	Computer Aided Production Management
CAPP	Computer Aided Process Planning
CATIA	Computer-Aided Three-Dimensional Interactive Application
CFD	Computational Fluid Dynamics
CIM	Computer Integrated Manufacturing
CLDATA	Cutter Location Data file
CNC	Computer Numeric Control
CPU	Central Processing Unit
CSCW	Computer Supported Cooperative work
DFS	Design For Sustainability
DFA	Design For Assembly
DFD	Design For Disassembly
DFM	Design For Manufacturing
DIY	Do It Yourself
DOF	Degree Of Freedom
EMP	Experience Music Project
ETO	Engineering To Order
FEM	Finite Element Modelling
GCS	Global Coordinate System
GT	Group Technology
HP	Hewlett Packard
IAAC	Institute for Advanced Architecture of Catalonia

Glossary

IBM	International Business Machines
ICT	Information and Communication Technologies
IT	Information Technology
JIT	Just In Time
KBE	Knowledge Based Engineering
LED	Light Emitting Diode
MBI	Modular Building Institute
MCD	Machine Control Data
MCU	Machine Control Unit
MHM	Massive Holz Mauer
MIT	Massachusetts Institute of Technology
MMC	Modern Methods of Construction
MTO	Make To Order
MTS	Manufacture To Stock
NASA	National Aeronautics and Space Administration
NC	Numerical Control
PC	Personal Computer
PDM	Product Data Management
QC	Quality Control
RAM	Random-Access Memory
SIP	Structural Insulated Panels
WWW	World Wide Web

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