DYNAMIC SIMULATION IN VIRTUAL ENVIRONMENTS AS AN EVALUATION TOOL FOR ARCHITECTURAL DESIGN

A THESIS
SUBMITTED TO THE DEPARTMENT OF
INTERIOR ARCHITECTURE AND ENVIRONMENTAL DESIGN
AND THE INSTITUTE OF ECONOMICS AND SOCIAL SCIENCES
OF BİLKENT UNIVERSITY
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
MASTER OF FINE ARTS

By
Şule Tagli
May, 1999

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I certify that I have read this thesis and that in my opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Fine Arts.

Prof. Dr. Bülent Özgüç (Principal Advisor)

I certify that I have read this thesis and that in my opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Fine Arts.

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I certify that I have read this thesis and that in my opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Fine Arts.

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ABSTRACT

DYNAMIC SIMULATION IN VIRTUAL ENVIRONMENTS AS AN EVALUATION TOOL FOR ARCHITECTURAL DESIGN

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M.F.A in Interior Architecture and Environmental Design
Supervisor: Prof. Dr. Bülent Özgüç
May, 1999

Prediction and evaluation of future performance of buildings are essential aspects of an efficient design process. This thesis aims to discuss dynamic simulation as a prediction and evaluation tool for architectural design. It is discussed that since buildings are living entities, whole life-cycles of buildings should be dynamically simulated in a highly visualized virtual environment to evaluate the future performance of prospective designs. The media of architectural design (traditional media: paper-based drawings and physical scale models; and digital media) are analyzed in terms of their capacity to support dynamic simulations. It is concluded that virtual reality systems and resulting virtual environments are yet the best media for the dynamic simulation of building designs. Some recent applications are mentioned and some important considerations for the future use of dynamic simulations in virtual environments are presented.

Key Words: Architectural Design, Dynamic Simulation, Virtual Environments.

ÖZET

SANAL ORTAMLARDA DİNAMİK BENZETİMİN MİMARİ TASARIMDA BİR DEĞERLENDİRME ARACI OLARAK KULLANILMASI

Şule Taşlı
İç Mimarlık ve Çevre Tasarımı Bölümü
Yüksek Lisans
Tez Yöneticisi: Prof. Dr. Bülent Özgüç
Mayıs, 1999

Yapı tasarımlarının gelecekteki performanslarının kestirilmesi ve değerlendirilmesi her başarılı tasarım sürecinin ayrılmaz bir parçasıdır. Bu tez dinamik benzetim modellerinin mimari tasarımda bir değerlendirme aracı olarak kullanılmasını tartışmayı amaçlamaktadır. Binaların gelecekteki performanslarını kestirebilmek ve değerlendirmek için binaların yaşam süreçleri görsel bir tasarım ortamında dinamik olarak benzetim modelleriyle inşa edilmelidir. Tez içerisinde mimari tasarım ortamları (geleneksel tasarım ortamları: çizimler ve maketler; ve sayısal tasarım ortamları) dinamik benzetim modellerini destekleme yeterliliğine göre analiz edilmektedir. Sonuç olarak sanal gerçeklik sistemleri ve onların yarattığı sanal ortamlar dinamik benzetimler için şu ana kadar bilinen en iyi ortamlar olarak ortaya konmaktadır. Bu konuyla ilgili en son uygulamalar ve gelecekteki olası uygulamalarla ilgili önemli konular tezin sonunda tartışılmaktadır.

Anahtar Kelimeler: Mimari Tasarım, Dinamik Benzetim Modelleri, Sanal Ortamlar.

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I dedicate this work to my parents Şükran and Mustafa Taşlı.

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INTRODUCTION

Although buildings have static structures, everything else related to architecture is dynamic. Environmental factors like sun, wind, and humidity change with time. People move through the buildings and they interact with them in numerous ways. Use patterns are likely to change in time and in some probabilities several events like fires, earthquakes, or floods may happen.

Evaluation of architectural designs against the criteria such as environmental factors, human factors, economy, etc. is an essential part of an efficient design process. This evaluation is usually conducted through a normative process. However, we discuss that architectural systems are rather complex to comprehend and to make predictions about future performance. In order to cope with such complex systems in architectural design a means of predicting the performance of buildings is needed. Dynamic simulation is building a model, that incorporates time, and using this model to test or experiment with designs. To conduct a dynamic simulation for architectural design, a medium is needed to "virtually" build and live in a building before the actual construction. A virtual environment or world in this sense is

1. The contents of some medium; 2. A space that exists in the mind of its creator, often manifested in some medium; 3. A description of a collection of objects in a

space, and the rules and relationships governing those objects (Sherman and Craig in Rowell, Definition 21).

Although the idea of simulation is not new for architectural design, simulation media (should) change due to the developments in technology. We believe that new technological developments should be explored by architects to enhance the methods of design process and quality of designs. This thesis aims to explore the potentials of dynamic simulations in virtual environments for architectural design in relation to the design media. Contents of the thesis are listed below.

Modeling complex phenomena is accepted as the domain of science and to produce dynamic simulations for architectural design, a methodological or scientific approach to design is needed. Therefore, Chapter 1 begins with an historical overview of methodological approach to architectural design. Several techniques and theories that were borrowed from operations research are also covered. Then, simulation as a methodology in design is discussed focusing on its use in architectural design.

Since the term "virtual environment" is defined as to be closely related to a "medium," modeling media in architectural design is discussed in Chapter 2. In order to obtain the maximum benefits from their design media, architects should be aware of the advantages and disadvantages of each medium. Hence, in this chapter each design medium is analyzed in terms of its capability to support dynamic simulation. The design media is categorized into two: traditional design media (drawings and physical models) and digital design media (computer graphics and CAAD). In the related literature, it is undoubtedly accepted that digital design media has revolutionized modeling in architectural design. Working with a computer, the architect does not cooperate with another person, but enters a new world. The discussion on digital design media begins with a brief historical overview of computer graphics and CAAD. Then, digital design media is covered according to the media dimension: one, two, three, and multi dimensional design media. Among them multi dimensional design media is observed to be the one best suited to dynamic simulation. Some promising modeling areas in multi dimensional media for architectural design are also discussed: computational fluid dynamics, mechanical modeling, and human modeling.

Virtual reality (VR) is a topic that has been discussed widely in 1990s. VR systems and resulting virtual environments (VEs) represent the ultimate development in the process of digitalization of architectural designs, which initially started with CAAD. We discuss that the promise of VEs is not due to the capabilities of VR systems produced so far, but it is due to the powerful vision underlying. The ability to produce real-time interactive simulation is a unique attribute of computer, and by this ability computer becomes an unprecedented medium. Virtual reality, as the most developed interface, is a promising medium for many applications in architectural design. In Chapter 3, VR is discussed as a tool for architectural design. The chapter begins with an overview of virtual reality including its brief history and types of VR systems. Then, applications of virtual environments in architectural design are covered.

In Chapter 4, the current and future applications in VEs in terms of dynamic simulations are discussed. There is an ongoing debate on the use of dynamic simulations in VEs on different fronts. Many industries such as aerospace, automotive, military, and medicine have already embraced dynamic simulations in VEs. Such systems are also penetrating into many other potentially fruitful areas like architectural design. Unfortunately, current architectural applications are limited in both the scope and amount, since, they are mostly produced by non-architects. In this chapter, current applications in other fields and in architecture are mentioned. Then, some important considerations for the future use of dynamic simulations in VEs for architectural design are discussed; suggestions for further research and conclusions are presented.

CHAPTER 1. MODELING AND SIMULATION IN ARCHITECTURAL DESIGN

1.1 An Historical Overview of Methodological Approach to Design

The origins of methodological approach to design dates back to post-second world war period, when the techniques from operations research, systems engineering, ergonomics, information theory and cybernetics began to penetrate many areas in order to cope with the pressing problems of the period. This movement had developed through a series of conferences in 1960s and 1970s (Cross 16).

Design methods movement claimed to bring systematic methods for designers in order to cope with the increased complexity of design process. Design was explained as a rational process composed of three steps: analysis, synthesis and evaluation. These steps were either formulated by linear flow charts, or by spiral forms representing reiterating sequence. Several techniques and theories were borrowed from operations research such as linear programming, network analysis, Monte Carlo method, value analysis, decision theory and theory of games. These may be summarized as follows:

Linear programming: Linear programming is perhaps the most frequently used of all operations research techniques. It is based on the fact that, in many problems, when the relationship between variables is plotted on a graph it proves to be linear. Although the number of architectural design problems that can be formulated as linear equations are limited, once it is done linear programming guarantees to find the optimum solution in a fixed number of steps (Radford and Gero 90).

Network analysis: Network analysis is conducted to analyze the activities within an overall project. An activity is defined as a task that takes time and usually consumes resources. Its starting and finishing points are known as events. Once the activities are defined, they are placed in logical sequences. Network analysis makes use of special charts in which each activity is represented by an arrow, and the events, which mark its start and finish, are marked by circles. In such a representation the critical path (the path to which attention must be paid if there is to be any shortening of the total schedule) of the scheduling operation is readily discernible. In architectural design, network analysis can be utilized, for example, for construction planning (Al, 1993) or for predicting the evacuation times of buildings in case of fire (Çağdaş and Sağlamer, 1995).

Queuing theory: Queuing theory as its name implies, is concerned with waiting of any kind. It has been developed to calculate for any given situation what kind of queue will result and how long the items will have to wait before service (Duckworth 34). In architectural design queuing theory can be used for lift siting, circulation analysis, canteen design, car parking provision, airport terminal layout, supermarket design, etc. (Reynolds 102).

Value analysis: Value analysis is an industrial technique by which the cost of the elements within a product is examined critically in relation to their utility. In value analysis, performance of each component of a product is assessed in relation to its cost, and the aim is to achieve the maximum utility for the minimum cost (Duckworth 42).

Decision theory: Decision theory can be defined as the application of scientific method to decision-making. It drew on experience from many other fields, particularly theory of games, cost accounting, information theory and logic. Decision-making can be defined as taking some course of action when several possibilities exist. According to decision theory decision-making is related to two different classes of things: performance of a physical system and a value system. Value system is often so complex that its components cannot be measured. Moreover, the condition under which decisions are made is not always certainty. If the probabilities of possible consequences of a decision are known then the decision is made under conditions of risk. Certainty is a special case of risk in which the probabilities are 0 or 1. Nevertheless, many decisions have to be made under circumstances in which the probabilities are not known: then it is said that these decisions are made under conditions of uncertainty. In order to cope with uncertainty, a predicting system that provides a list of possible outcomes for each action is needed. All the resources of simulation, model building, experiment and test can be used in a predicting system (Duckworth 72-82).

Theory of games: Theory of games is an extension of decision theory where instead of one's choice of action being conditional on the possibilities of several outcomes, it is determined by the possible alternative actions of an opponent playing the same game (Duckworth 83). A game in this sense is a set of rules which determine what a player may do, what is to be won and who wins it, depending on what the players have chosen to do. Gaming can be effectively used in urban planning to enhance collaborative design (Brown et. al., 1998) and (Goodfellow,. 1998).

Monte Carlo method: Monte Carlo method is a kind of simulation in operations research. As its name implies, it is concerned with situations in which events occur at random. Monte Carlo method employs random numbers for solving stochastic or deterministic problems where passage of time plays no role. It can be used for building cost estimation (Yaylagül, 1994) and (Arpacı, 1995).

Although all these techniques remained influential, even the early pioneers of the design methods movement began to reject it in 1970's (Cross 16). Mitchell identifies three main areas that led to the failure of the "first generation" design methods. One of them is the apparent complexity of much of the early work on the subject. Mitchell claims that designers are well known for their aversion to science, so the early complex diagrams and dense text of design methodology looked too analytical, too abstract, too inapplicable to the task of design as then understood. According to Mitchell, another reason for the failure of design methods was that design methods seem to have been embraced only by those who mistakenly believed design to be a completely explicable, rational proposition. On the other hand, the principal failure of design methods was identified by Mitchell as a social one. He explains that design methodologists tended to view their work as a "good thing" that would naturally be taken up once publicized. They gave insufficient attention to the profound social implications of design methods. Specifically, adoption of design methods as they were originally conceived would entail users being "reeducated," organizational changes in design offices, and design methodologists changing their own ideas and roles. In each case the people with the power to change were disinclined to do so (C. Mitchell 47-50).

Heath's explanations of the failure of "first generation" design methods are similar to that of Mitchell. He claims that design methodologists failed to reduce design time or cost, while providing minimal improvements in designs. The problems they could solve were often only very simple ones, the sort of problems that cropped up after the architects had done all the really hard work anyway (Heath in Stevens 320).

Despite all the failures of the "first generation" design methods, the seeds of the most advanced approach to user-sensitive design yet developed is implicit in the philosophy of early design methods. The recognition of the systems related to architecture had its origins in this movement and the idea of "simulation" for architectural design dates back to this period (C. Mitchell 51).

In 1970's the criticism of first generation design methods led to a new understanding of design as an argumentative process. Architectural design was considered as a participatory process in which designers are partners with the problem owners (clients, customers, users, and community) (Lang 43). The main criticism of the early models of design process can be summarized in the following way: design is not a strictly sequential process and design problems are "ill-defined" and a linear step-by-step procedure cannot be applied to them. "Ill-defined" refers to the difficulty of articulating what the problem is and of determining whether or not a design proposal is really a solution to a problem. Ill-defined problems are characterized as follows: they have no definitive formulation and their formulations tend to change during the process; they have no definitive set of operations to solve them or to evaluate solutions; knowledge required for solving them is partial and sometimes contradictory (W. Mitchell, Computer 60-62).

Consideration of design as an "ill-defined" problem led to the recognition of satisfactory or appropriate solution types. Simon in his famous book The Sciences of Artificial introduced the notion of "satisficing" solutions. However, this approach tends to be more relevant to architecture and planning than engineering and industrial design. Therefore, design methodology in architecture and engineering appeared to diverge from each other in the 1970s and 1980s (Cross 17).

In late 1980s and 1990s, there has been a broad renewal of interest in design methodology, especially in Artificial Intelligence (AI) developments (Cross 17). AI is a branch of computer science that deals with the development of computer programs which solve problems in a way that would be considered intelligent if done by a human (Waterman 5). It is claimed that, AI is a means of understanding a problem itself, besides solving it, and because of this property and the possibility of incremental growth in AI programs, AI is a helpful device for ill-understood problems like architectural ones (Flemming 1-5). Knowledge-based systems have been produced for architectural design by the help of the AI techniques. The aim of these systems has been design automation and/or electronic design assistance.

1.2 Modeling

1.2.1 Definition

A model can be defined as a representation of relevant characteristics of a reality. In other words, it is a means of expressing certain characteristics of an object, system or situation that exists, existed, or might exist (Echenique in Rowe 163).

Rowe identifies five steps in the process of model making. First step is the existence of an object, setting, or a system that is of interest. Second step is the clearly expressed intention, enabling the selection of appropriate characteristics of the object, setting, or system. Third step is the process of observation and abstraction enabling the reality in question to be observed in relation to selected variables. Fourth step is the process of translation, enabling the creation of a suitable conceptual framework for organizing the information. The final step is the validation of the model. It is the process of making sure the computer model accurately represents the object, setting, or system being studied (Rowe 164).

Discussing models, it should be always in mind that no matter how much effort goes into its construction, a model could never be a perfect or complete representation of reality, because human beings do not have perfect information about the real world. Therefore, the validity and usefulness of dynamic models should be judged not against an imaginary perfection, but in comparison with the mental and descriptive models that could be used otherwise (Forrester in Radford and Gero 16).

Architectural design is a purposeful activity that necessitates decisions made about physical form of buildings and spaces in response to needs and goals related to the building's intended purposes (Radford and Gero 19). Architects always deal with some kind of representation or model while designing. In fact, architectural design is a modeling process (Şenyapılı and Özgüç, Interface 106). An architectural model may exist only in the mind of the architect, but normally it needs to be manifested in some medium (paper, cardboard, digital media, etc.). Modeling media in architectural design are discussed in the Chapter 2.

1.2.2 Classifications of Models

In this part of the thesis some classifications of models are discussed in a broad sense to encompass a range of models in addition to architectural ones. The use of the word "model" in this sense stems from the field of operations research. Churchman, Ackoff and Arnoff in their early Introduction to Operational Research identify three types of models: Iconic, analogue and symbolic. By its definition, an iconic model "looks like" what it represents. For example, photographs, paintings or sculptures may provide iconic models of people, objects or scenes. On the other hand, in an analog model, the various properties of the original may be represented by properties of quite different kinds in the model. A map for instance, is an analogue model in this sense: roads and political boundaries are represented by lines, different kinds of land use by different kinds of hatching or color, and so on. Lastly, symbolic models are made in terms of numbers or of symbols from logic. Mathematical models of all kinds are symbolic models and symbolic models generally are the basis of computing. Mathematical models can be classified as analytical and simulation models. In analytical models, values of functions can be determined directly by performing algebraic operations. On the other hand, with simulation models values of functions are not so readily determinable, they can only be discovered by simulating and observing the behavior of the system in an appropriate way (W. Mitchell, Computer 38-40).

Broadbent mentions descriptive and normative models; that is models concerned with describing a reality from a particular point of view, and with indicating what might be expected if certain clearly defined condition are fulfilled. Descriptive models can be static (i.e. constant over time) or dynamic (i.e. concerned with things which change over time). Normative models on the other hand, are used to describe an unfamiliar situation by drawing analogies with a familiar one and they may be used for prediction (Broadbent 90).

Rowe proposes a hierarchical classification of four types of models, according to the general purposes of their application. They are descriptive models, predictive models, explorative models and planning models. According to Rowe, the principal intention behind a descriptive model is explanation of phenomena in the domain of interest and descriptive model is logically essential for any other three types. On the other hand the purpose of a predictive model is to give a forecast of the temporal disposition of the phenomenon under study. A planning model necessarily incorporates prediction, but it is extended to allow for the evaluation of predicted outcomes in terms of goals. In other words, this type of model is primarily developed for simulating the effects of different decisions and evaluating those decisions or strategies against a specified goal structure (Rowe 166-68).

1.3 Simulation as a Methodology in Design

1.3.1 Definition

Simulation is the use of a model to develop conclusions that provide insight on the behavior of any real world system or it can be defined as the use of a model to experiment (test) with it. Therefore simulation includes not only model development but also the use of it. (McHaney 2).

Computer simulation is a branch of applied mathematics that is widely used by many disciplines. It is used in different senses to study a variety of systems that may be classified as continuous vs. discrete, deterministic vs. stochastic or dynamic vs. steady state. Simulation is used within many areas, so it is considered to be a methodology. The process of describing many complex real world systems using only analytical or mathematical models can be difficult or even impossible in some cases. This necessitates the employment of a more sophisticated tool such as a computer simulation. Using a computer to imitate or simulate the operations of a real world process or facility requires that a set of assumptions taking the form of logical or mathematical relationships be developed and shaped into a model (Nance and Overstreet 40).

The main advantage in using simulation is the reduction of risk involved with implementing a new system or modifying an existing one. Simulation enables several “what if” scenarios constructed into a model so that several alternatives can be tested prior to realization. By this way, a detailed simulation may reveal unforeseen problems that exist in a system’s design. Moreover, simulation increases the overall system knowledge. Because, knowledge required for modeling complex systems is usually complex and divergent. To develop a working simulation, all this knowledge needs to be gathered together and organized. This process of collection and organization inevitably cause an increase in knowledge on the system being studied. Finally, when a model is developed, simulation may provide speed in analysis if time is compressed in the simulation model and it enhances creativity by enabling comparison of new and somewhat risky solutions with conservative ones (McHaney 41-43).

Computer simulation can be an expensive and complicated technique. McHaney describes some situations warranting the use of computer simulations as:

1. The real system does not exist and it is too costly, time-consuming, hazardous, or simply impossible to build a prototype.
2. The real system exists but experimentation is expensive, hazardous, or seriously disruptive.
3. A forecasting model is required that would analyze long periods of time in a compressed format.

4. Mathematical modeling of the system has no practical analytical or numeric solutions (McHaney 3).

1.3.2 Simulation for Architectural Design

Architectural design deals with many intermingling systems (environmental, psychological, economical, cultural, etc.). Therefore, simulation as a means of imitating a real system and predicting its behavior, is an essential phase of an efficient design process (Bertol 43). In fact, architectural design should be considered as an interface between people and buildings and it should respond to the needs of the people and environmental conditions. Unfortunately, it is observed that this fundamental role of design as an interface has been forgotten for most of the cases. It is not only because of the ignorance of the architects, but also of the complexity of the factors that are essential to design but difficult to incorporate the design process. These factors are becoming more and more complex in time, therefore computers should be used to simulate them (Iwaki 122-23; C. Mitchell 44).

Jones claims that designers should be dealing not only with the "things" but also with the functions and uses of things, the "systems" into which they are organized, or the "environments" in which they operate. Moreover, he claims that the change in scale, from physical objects to systems and environments, is also a change from designing-in-space to designing-in-space-and-time. As the scale of designing is increased, the way things are used, their life cycles become as much designed as do their shapes (Jones xxxi-xxxiii). However, incorporating dynamic systems in design is not an easy work. It can only be achieved by the use of dynamic simulations generated by computers.

Robertson also recognizes the "non-material" aspects of design and proposes the concept of "4D design" instead of traditional design process. The fourth dimension refers to time and 4D design is described as "the dynamic form resulting from the design of the behavior of artifacts and people in relation to each other and their environment." Based on the classical assumption of "science" and "art" aspects of design, 4D design focuses on dynamic form that incorporates knowledge of "kinetic art" and particularly performing arts at one extreme and dynamics within engineering science at the other (A. Robertson 149-50).

In general, there are two basic approaches to representing knowledge in evaluative methods in architecture. The first one is the rule or norm that are manifested in checklists, guidelines, and rules of thumb. The second approach is modeling and simulation. These two approaches are compared by many authors. According to Koutamanis the rule-based approach although valuable in some aspects, has a limited capacity to respond to the uniqueness of each situation in architectural design. Simulation can be a more useful tool for extreme or unexpected cases (Koutamanis 97-101).

Steinfeld claims that in practice of architecture, knowledge about many systems is represented in design activities primarily through a normative process. Such knowledge is based on architect's own experience of what has worked in the past, or that of some other designers' embodied in existing buildings that can be observed. However, if the normative approach is used exclusively, it is very limited due to the general nature of this knowledge (Steinfeld 330). Since any departure from a solution that has worked before leaves the architect with no point of reference –She cannot be sure that her new design will work-, original solutions are discouraged and the basic designs tend to remain unchanged. Remaining designs unchanged, the less obvious mistakes can become "fossilized" and carried from one building to the next. On the other hand, simulation approach enables testing new and innovative designs and comparing them with the conservative ones by reducing the risk of implementing a totally new design. Therefore, simulation enhances creativity for architectural design (Reynolds 101).

Stevens compares simulation with rules of thumb and identifies two important problems in relying on rules of thumb. First, a rule of thumb is useless as an aid to understanding, this means anything cannot be learned if it fails. Since the rule was developed from past experience -because there is no theoretical guide- a failure of a rule cannot lead to any advance in providing better rules. Second, rules of thumb are often incomplete, partial or contradictory. On the other hand, a simulation model has an important advantage over a rule of thumb; such a model explicitly lay down its assumptions. Therefore, it can be controlled and criticized at each step of its development (Stevens 281-82).

Negroponte forecasts in 1975 book The Architecture Machine that "Someday designers will be able to subject their projects to the simulations of an entire day or week or year of such events as use patterns and fast time changes in activity allocations. On display devices, designers will be able to see the incidence of traffic jams, the occurrence of sprawl, or sweltering inhabitants searching for shade." According to him the simulation of events can benefit the architect in two ways. If the designer does not fully understand the behavioral aspects of an event she can play with rules and regulations, searching for recognizable activity patterns. In other words, from empirical knowledge of a set of actions and reactions for specific environments, a designer could inductively compose algorithms applicable in other contexts. The second benefit of simulations is pretesting; assuming the model is correct, designs can be tested (Negroponte 47-8).

As mentioned before, although it is very powerful, simulation can be an expensive technique. Reynolds claims that simulation cannot usually be said to save the architect money, but its justification is a better design and better use of the client's budget (Reynolds 110). The previously mentioned arguments on situations warranting the use of computer simulations by McHaney can be translated to the use of simulation for architectural design.

Then, the reasons for using simulation for architectural design are presented below:

1. Unlike in other industries, it is impossible to build a first realistic prototype, because normally every building is unique.

2. Real experiments can be dangerous (e.g. fire evacuation, thermal comfort, etc.)

3. Since buildings are living entities, forecasting models are needed to analyze periods in building life cycle in a compressed format.

4. Mathematical modeling of most of the architectural systems does not lend themselves to practical analytical or numeric solutions.

Nevertheless, it should be in mind that simulation makes use of models and models give us only a partial picture of the reality. Therefore, simulation provides only approximate answers. Even to have these approximate answers, the model used for simulation needs to be validated. Validation can be a difficult task for some cases. Moreover, simulation is not an optimization tool. Answers to questions can be provided but these answers are not always the optimal solutions (Reynolds 102).

CHAPTER 2. MODELING MEDIA IN ARCHITECTURAL DESIGN

In architectural design, modeling is a process, either mental or externalized, of translating conceptual ideas into visual forms. Although at its root the idea of modeling has been the same throughout the history, it has taken on many forms of expression. These expressions are mainly the result of technological advances in producing imagery.

Burden classifies design media in architectural design as follows:
1. Drawings 2. Physical models 3. Special techniques (photogrammetry, holography, etc.) 4. Computer graphics and 5. Sequential simulation (combination of computer graphics and video) (Burden VI-VII).

Abbo identifies three types of models for architectural design:

1. Two dimensional models; drawings, photographs, slides, films and computer graphics
2. Models that give three dimensional impressions such as stereoscopic slides, holograms and virtual reality
3. Three-dimensional physical models either scaled or full-size.

Then he explains that drawings, three dimensional scale models, computer graphics and virtual reality are the most widely used types (Abbo 70).

In this section, traditional design media (drawings and physical models) and digital design media are analyzed in terms of their capacity to support dynamic simulations. Medium's ability to represent time dimension and the systems that architects have to deal with beyond the building geometry are the main concerns. Virtual reality as a modeling and simulation tool is covered in Chapter 3 and 4.

2.1 Traditional Design Media: Drawings and Physical Models

2.1.1. Drawings

Paper-based drawing is perhaps the oldest of today's modeling media. Use of computer graphics is already widespread and continuously increasing, but even today the debate of replacing paper-based drawing with computer graphics is still on (Sullivan, Holdouts 126-28). Paper-based drawing is mostly used at the earlier stages of design while sketching and producing design concepts. The main reason for this is the lack of support for sketching in most of the CAD software (Palmer 120). Dorsey and McMillan compares the use of traditional design media with that of digital design media and they claim that traditional media is preferred by architects at that stage of design development. Since traditional media is pliant, flexible and forgiving and by their nature, they encourage exploration and iteration. In contrast, the representations used in CAAD systems tend to be rigid and precise that makes them inefficient at the earlier stages of design (Dorsey and McMillan 46).

On the other hand, although widely used by the architects, drawings are inefficient to support simulations for architectural design. A drawing is a rather abstract representation that is not related to the context of use. Therefore, it is not a proper medium for testing and refinement of designs. Jones contrasts the rigidity and limitations of "design-by-drawing" with the responsiveness of the craft process. He explains that trial and error is separated from production by using a scale drawing in place of the product as the medium of experiment and change. The scope for using drawings as a means of producing well adapted designs is limited. Because, "The principle of deciding the form of the whole before the details have been explored outside the mind of the chief designer does not work in novel situations for which the necessary experience cannot be contained within the mind of one person." Jones claims that by design-by-drawing, designers focus on visual articulation and ignore everything non-visual that the scale drawing fails to represent (Jones in C. Mitchell, 41-43).

2.1.2 Physical models

Three-dimensional physical scale model is also an old and widely used means of representing designs in architecture. By working directly in space, although at small scale, concepts are formed and reshaped as a result of their exploration in three dimensions. In this way, new options might appear to the designer trapped within the confines of the paper. However, one significant disadvantage of scale models is their rich displays of spatial intricacy that cause a "miniaturism" –an attitude associated with the discrepancy between human and scale model scales-. Therefore, the significance of an idea in a scale model may be lost or reduced when enlarged to full size (Porter 107-12).

As a means of surmounting the scale barrier and having dynamic views of physical scale models, modelscopes can be used. Modelscopes are miniature periscopes inserted into models. Movement through model space can be simulated by panning and tracking and these views can be photographed by attaching a camera. Similarly, a video camera can be attached to modelscopes to have a sequential view. Video-based simulators provide better picture quality compared to photograph-based simulators (Burden 76-77).

Full scale models or experimental mock-ups are alternatives to physical scale models. They are usually constructed from materials other than those intended for the ultimate form (e.g. painted canvas and timber). A common practice in United States is the on site construction of one floor of a skyscraper before building commences, the prototype being utilized for experiments with lighting, services detailing, color schemes and furniture layout. For mass production of housing, full size mock-ups of designs provide better public participation in their designs. Layman who find difficulty in reading architect's drawings may easily understand designs by the help of the mock-ups. Depending upon the nature of the mock-up, all visual cues can be represented in space besides tactile information. A mock-up is also capable of introducing the opportunity for the designer to articulate space against the reactions of the intended users. However, the use of full-scale models for architectural design is extremely limited due to the very high costs of such models. They can only be applied to repetitive, small units when such modeling is affordable (Porter 132-36).

2.2 Digital Design Media: Computer Graphics and Computer Aided Architectural Design

Computer graphics and CAAD revolutionized modeling media in architectural design, since a digital model of a design is capable of representing a design much better than traditional media. One basic advantage of a computer model is its flexibility. Designs can easily be modified, observed in different settings with different point of views, even by "walking" through them. However, the most important advantage of digital media is the opportunity of testing buildings before they are built (Greenberg, Architecture 541). Batty claims that the single most important difference between digital computation and other media rests in the concept of simulation. Digital simulation enables structured manipulation of virtual worlds that can be manipulated easily in comparison with other forms of model making (Batty 254).

Şenyapılı compares traditional design media with the digital one in terms of capacity to represent the design model formed in the designer's mind. She claims that both paper-based drawings and physical models fail to represent mental design model, because they do not have the capacity for performance analysis and rapid changes of design. However, digital design media has the capacity to represent the whole design process and with the emergence of digital media "the model became the design method itself" (Şenyapılı, True Model 135).

Mitchell and McCullough in their excellent book Digital Design Media categorize digital design media by media "dimension." Excluding practical computation and numerical modeling tools such as databases and spreadsheets they organize their discussion of software not by category or task, but by the dimension of the media. Their classification is presented below:

1. One-dimensional media: words, texts ,and sounds
2. Two-dimensional media: images, drafted lines, polygons, plans and maps
3. Three-dimensional media: wire frame models, surfaces and renderings, and assemblies of solids
4. Multi-dimensional media: motion models, animation, and hypermedia

In this section digital design media is discussed according to this classification. The discussion of the digital design media and its uses and limitations for architectural design follows a brief history of CAAD.

2.2.1 A Brief History of Digital Design Media

Although it has been revolutionary to the theory and practice of architectural design, the use of computers in architecture has a relatively recent history. For the scope of this thesis the history of computer aided architectural design is summarized in this section according to the following structure:

1. Drafting and mechanization of design process
2. Knowledge based systems and AI in design
3. 3D modeling, visualization in motion and virtual reality
4. Object-oriented 3D single building models

The idea of communicating in graphical form and of producing graphics with a computer was born during the 1950s, almost at the same time as the introduction of the first commercially available computers. In 1963 Ivan Sutherland developed an interactive computer graphics system called "Sketchpad" that displays drawings and allows manipulation of graphic objects. Another important development of the period was due to Steve Coons who introduced surface patch techniques that laid the basis for solid modeling. Steve Coons was the originator of the term "Computer Aided Design" (Ferrante et al. 4). In 1960s and 1970s some experimental interactive graphics computer aided design systems were developed like COPLANNER (Souder and Clark, 1964) and URBAN 5 (Negroponte and Groisser, 1970).

From 1970s onwards, the cost of hardware started to decrease. Pen plotters, graphic tablets, digitizers, light pens and different devices for cursor control like trackball and joystick became typical computer graphics hardware during this period. By the mid 1970s CAD/CAM became an industry. Several ambitious large-scale computer aided design systems were established like CEDAR, HARNESS, OXSYS, CARBS, SSHA, etc. These were specialized systems developed to serve large public sector construction organizations (W. Mitchell, Computer 16-17).

During the 1980's integrated CAD/CAM systems that combine computer graphics and numerical processes emerged. Nevertheless, computer systems were still very expensive until the mid-1980s and only the largest firms could afford their use. In the second half of the 1980s, by the development of first inexpensive personal computers, mass-market CAD systems appeared. The PC has brought automation to firms of all sizes. Therefore, the early commercial CAD systems were simplified and standardized to minimize the need for installation, training and support services. There has been a shift from vendors with proprietary hardware-plus-software packages to an open market with thousands of software developers competing on multiple platforms. Moreover, they mimicked the traditional tools (pens, paper, paint brushes, etc.) The negative effect of early commercial CAAD systems was to establish a "banal" or rather simplistic conception of CAAD systems in the minds of the architects. CAAD systems were seen as simple devices for manipulating graphics just like word processors for manipulating texts (W. Mitchell, Afterword 481-83). Therefore, CAAD gained acceptance as a term referring to automated drafting with the "D" in "CAAD" actually to be read as "drafting" (Ohira 7)

Knowledge-based systems gained acceptance in the late 1980s to shift the computer aid in architecture from mere drafting to design. They have created great enthusiasm among many academicians who view design as a "knowledge-based" activity. Many of them claimed that knowledge-based design systems would push aside the other CAAD systems and would introduce new building modeling systems that are capable of producing original solutions with expert languages (W. Mitchell, Paradigms 379-83).

Despite the hype that was created, knowledge-based systems failed to achieve their goal as "intelligent design assistants" for the practice. In architectural offices CAAD has been used primarily for production drawings, or rendered presentation drawings. The main benefit of CAAD to architectural design remained as efficiency and production quality. Recognizing these issues, it began to be claimed that computer should be used as a "medium of design" instead of a "thinking machine." The supporters of this idea claimed that architectural CAD should be predominantly visual. It should be able to manipulate or simulate solid, void, and plane; light, color, and texture; and acoustics. Instead of evaluating designs formally against predefined objectives, computer modeling and simulation should be used in an evaluation process that incorporates both the designer and the client (Richens 307-8).

3D modeling, visualization in motion and virtual reality introduced a new dimension to architectural presentation in 1990s (Emmett 30). -The issue of virtual reality is covered in Chapter 3.- Demands of clients for 3D modeling and visualization in motion has been the main driving force for the widespread use of such tools. The public is exposed to high-end graphics on a regular basis in games, on TV and in movies. It is this type of output that most of the clients began to demand in 1990s. As a result, to edge out the competition architects have had to use advanced modeling and animation (Mahoney, Moving 20-22). In 1998, virtual reality, especially the screen-based type, has already become a common presentation practice for many offices in United States. Such systems have been used for previewing numerous aspects of designs and teaching architects where designs fail (Mays, Making 162-63).

In the second half of 1990s several 3D-based object-oriented software products have emerged. The basic idea of object-oriented software is to combine software and data into the same object i.e. combination of the data describing the object and the operations related to it. In fact, this was an old idea that dates back to 1960s. Objects originated in the simulation programming languages like Smalltalk and Simula. Such software has enabled the definition of objects in a hierarchy so that an object can inherit the properties of its "parent" object (Sanders 104-6). The benefit of object-oriented software to architecture is clear "because object-oriented design is what architecture is all about." Architects can use object-oriented software to describe the attributes and behavior of a broad range of architectural objects most of which are well described by their interfaces (Sanders 108-10).

The emergence of 3D-based object-oriented commercial software for architectural design has been viewed by many authors as the result of a paradigm shift from automation to simulation of designs. The primary reason for the long time required reaching such a point is that architectural design is an extremely complex process. In such products a single 3D building model is produced by designing directly in three dimensions. 2D drawings are produced from the 3D model. In this way, the 3D building model itself becomes the contract document, instead of drawings (Novitski 22-28). Advantages of 3D-based object-oriented architectural design software are summarized below.

1. Simulation support for the whole building life cycle.

With these systems, the model becomes an easily searchable electronic simulation of the physical building that grows more valuable in time. With data attached to three-dimensional building elements, cost estimating, maintenance plans, and monitoring for safety and security will be far easier (Mays, Longer 154).

2. Help to maintain the architect's copyright of design.

A 3D-based firm owns and retains a computer model that can be locked, unlike a paper-based practice that transmits the design as a set of bluelines that can be easily copied. Unless arrangements are made to sell the digital building to the client, not just the right to use it for construction, the original architect will have a competitive advantage in winning remodeling and facilities management work for that building for the whole life of the building (Novitski 27).

3. Support for collaboration.

The need for collaboration with clients and other professionals involved in design process has been increasing. In a survey of large architectural firms made in summer 1998, 94 percent of principals responding ranked "collaboration throughout the building process" over "individual productivity" in their five year goals. This is a significant shift in architects' perceived technological needs. Earlier surveys have tended to show 80 to 90 percent of respondents focused on the desire for better drafting and drawing systems. 3D-based object-oriented software supports collaboration by sharing a single model among professionals dealing with the project (Ross 175).

2.2.2 One- and Two-dimensional Design Media

Sound sequences and texts are one-dimensional structures of data elements in which each element has a unique predecessor and successor. One-dimensional structures constitute the basis of computing. Although their direct use in architecture may be less than that of other occupations, the two-dimensional, three-dimensional and four-dimensional structures that concern designers must always be translated into one-dimensional structures at some level usually invisible to the computer user (Mitchell and McCullough 70-71).

Two-dimensional media includes bitmapped images, drafted lines, polygons, plans and maps. A bitmapped image is a picture that is encoded and stored as a rectangular array of integers. The rectangular array is called a raster grid, a single row from the grid is called a raster line, and a single square element is called a pixel (standing for "picture element.") Systems for capturing, storing, manipulating and displaying such images are known as image processing and paint systems and they have a wide range of applications in design. Nevertheless, a bitmap is just a numerical equivalent of a picture i.e. it may represent a painting or a photograph. Therefore, image-processing software is incapable of showing detail of indefinitely fine resolution, showing objects in scene from other than original view point, or providing manipulative operations on objects that depend on knowledge of the internal structure of the manipulated object (Kerlow and Rosebush 14-15).

On the other hand, computer graphics software that is designed for use in technical drafting provides tools for precise manipulation and accurate presentation of geometric entities. Such systems make use of coordinate systems. Points are described in terms of x and y coordinates; lines are described in terms pairs of points and so on. Moreover, they provide basic tools for inserting, selecting, and deleting lines, and some other additional tools like break, extend and trim operations. Similarly, they provide tools for creating, transforming and deleting complex shapes. Some basic geometric transformations are translation, rotation, scaling, reflection, stretching, shearing, projection and deformation (Bertol 74-5).

A model that consists of a set of two-dimensional line drawings of a building is a highly abstracted representation (like a paper-based drawing). Although it explicitly represents the building geometry and appropriately structures the information related to a particular stage in building design, it deals with only a few aspects of a very complex reality. Therefore, there are many important design activities that it cannot support. The main disadvantage of such an abstract representation is that the viewer must "fill in" a great deal of information to interpret two-dimensional shapes as projections of three-dimensional objects. Misinterpretation is possible. Mitchell and McCullough claims that the main advantage of using computer for drafting is that "static, location-addressable, fixed format, non-machine-analyzable design representations give way to dynamic, content addressable, variable-format, machine analyzable representations." Hence, faster production of finished drawings and efficiency in drawing production are only useful by products but not the aim of drafting with computers (Mitchell and McCullough 131-33).

Unlike drafting systems that represent the boundaries of things by lines, polygon-modeling systems deal with the spaces between these boundaries. Therefore they are used for producing drawings consisting of areas of color and pattern and for working on space-planning, analysis and management problems. Plan-based and map-based information systems can be produced by establishing cross-references between polygon files and files of non-geometric information (Mitchell and McCullough 147-52)

2.2.3 Three-dimensional Design Media

Three-dimensional design media includes wireframe models, surface models and solid models. Similar to that of two-dimensional media there are two ways to represent models in three-dimensional media: voxel representation and boundary representation. Voxels (volumetric elements) are three-dimensional arrays of data points. For this purpose a cuboid is subdivided into cubic voxels just like a rectangle is divided into square pixels. However, for designers' purposes voxel representations suffer from the same sorts of limitations as the bitmapped images as considered in 2.2.2. They are low-level, unstructured, imprecise, and inefficient in use of available computational resources. For greater precision and economy and to provide higher level design operations, three-dimensional models should be represented in terms of x, y, z coordinates, bounding lines and surfaces (Mitchell and McCullough 238-39)

Wireframe models represent buildings as collections of lines in three-dimensional space that had been projected in perspective onto a two-dimensional picture plane. A wireframe model provides a more complete representation of building geometry than a collection of two-dimensional drafted lines. Most importantly, a wireframe model can support forms of design exploration, geometric problem solving and measurement and analysis that are very difficult or impossible with two-dimensional representations (Bertol 71).

Surface-modeling systems represent buildings not in terms of their edge lines, but as collections of surfaces described by their outlines and curvatures. Such systems can produce not only wire frame images, but also hidden surface views showing opaque surfaces in light. They allow information specifying surface properties (color, specularity, texture, etc.) to be associated with surface elements and allow the light sources to be specified. Surface models provide much more realistic images than a wireframe view. Amor claims that advanced rendering software has great benefits for architectural design. Since, it can bring the virtual environment (computer rendering) closer than anything else to the built environment. Then he mentions six aspects of visualization that can be performed much more effectively with computer technology than with traditional tools: unlimited perspectives, material appearance, surface characteristics, transparency and translucency, lighting and context of the project (Amor 19-20).

Solid modeling systems represent buildings as assemblies of solids. The displays produced by solid modeling systems may look like the displays produced by wireframe or surface modeling systems, but the underlying geometric databases are very different. Therefore, solid modeling systems have powerful geometry-editing operations not available in wireframe or surface systems and they also have some additional data extraction and analysis possibilities. For example, solid models are particularly appropriate for volumetric and engineering analysis. Properties of closed solids (volumes, surface areas, centers of gravity, moments of inertia, etc.) can be easily calculated by such systems. Therefore, a solid modeling system can be used to measure the amount of material to be cast in a form, to measure the volume of an auditorium for heating and cooling and acoustical analysis, or to measure the volume of a building for urban design analysis. For detailed analysis of engineering properties, solids may be broken up into small pieces, known as finite elements. Advanced solid modeling systems provide algorithms for automatically constructing finite-element meshes from boundary models. Finite-element analysis procedures can be used to produce detailed and accurate analysis of structural properties, thermal properties and so on (Mitchell and McCullough 268-69).

2.2.4 Multi-dimensional Design Media

Multi-dimensional media includes motion models, animation and hypermedia. A digital model of a three-dimensional solid in motion over some time interval constitutes a motion model that has three space coordinates and one time coordinate. Each four-dimensional data point is called a "hypervoxel." Such four-dimensional objects are very difficult to visualize directly. Mitchell and McCullough explain two ways to visualize four-dimensional objects. One of them is collapsing a four-dimensional model to a three-dimensional one by collapsing the time dimension. The other way is to select a plane, then collapse the three-dimensional scene onto that plane at successive moments. This produces a sequence of two-dimensional bitmapped images i.e. frames of a digital movie (Mitchell and McCullough 271-73). In practice, software for modeling solids in motion typically provides the operation of keyframing for specifying such four-dimensional models. A pair of key frames show a three-dimensional solid at two moments in time. These two time points state the beginning and end of a motion sequence. Motion modeling software simulates the movement of object between these two moments (Mitchell and McCullough 275).

It can be claimed that motion models of three-dimensional assemblies are relatively costly to build, modify, and maintain and they are not necessary because the analyses conducted by them can also be produced from much more abstract means. Nevertheless, the costs of building and maintaining motion models are dropping as the technology advances. Most importantly, the demands for more through evaluation of designs are growing.

For most of the industries motion models of products, that are called digital prototypes, are replacing the place of physical prototypes. Digital prototyping is producing a computer model of a product, instead of a physical one, for product evaluation and testing. With digital prototyping tools, product designs can be tested and evaluated for problems during the design cycle rather than at the end of it. Furthermore, digital prototypes provide the ability to perform multiple what-ifs, run tests, and other analyses of the behavior of a product design in a way that may not even be possible using conventional methods. Digital prototypes, for example, can be used in computer-based simulations that evaluate how a product will perform in varied environments like extreme temperatures, specific atmospheric conditions, or other test settings that would be difficult or even impossible to duplicate for evaluating a physical prototype (Rowell, Prototyping 55-58). Virtual reality technology is also used to create digital prototypes called "virtual prototypes." This type of modeling is discussed in 4.1.1.

There is a growing interest in advanced motion modeling software in architecture too. In the early 1990s architectural firms that used 3D computer renderings and/or animations to present their prospective designs were unique enough that they could almost win a bid on the novelty of their approach alone. This situation has changed toward the end of the decade. Architects have been forced to use motion models by their clients. By animating rendered CAAD sequences, architects, in one sense, turned out to be "movie directors" that design a four-dimensional experience. In other words, the architect has shifted from a static design stance to one that is cinematic (Porter 122-26). Nevertheless, producing a "building movie" represents only the first step in opportunities for "virtually" building. Clients' demands for realistic simulation of design performance has been increasing and in many cases, architects have to explore new technologies to respond these demands (Mahoney, Moving 21).

There may be three main areas of modeling in multi-dimensional media that have potential benefits for architectural design:

1. Computational fluid dynamics
2. Mechanical dynamics
3. Ergonomic modeling

These areas of modeling are covered in the following parts.

2.2.4.1 Computational Fluid Dynamics

Computational fluid dynamics solves the equations that govern fluid flow (momentum, energy, and mass) and translates the numeric solutions into easy-to-read graphics. Computational fluid dynamics, by its definition, involves patterns of change over time and space. To understand even simple phenomena often requires several types of representation. Truly informative displays must be dynamic. Through animation, icons can be watched moving and changing over time. Techniques for the display of flows include vectors, streamlines, streaklines, and particle paths (Richards 282).

Computational fluid dynamics can be used in architectural design to predict air flow speed, pressure, temperature, turbulence levels, heat transfer, a potential fire's progress and concentration of contaminants such as smoke. Although it was first used in the early 1970s to predict air movement in buildings, commercial software programs targeted the modeling techniques for building applications are relatively new (Sullivan, Modeling 163-64).

Battle and McCarthy discuss the use of advanced computer software for simulating natural forces like temperature and air movement in buildings. They explain that architects may use such tools to expand their interpretation of natural forces with form. Such computer simulations do not claim to provide architectural solutions for the built form but claim to be more realistic representations for predicting the future environmental performance of buildings than any artist's impression submitted in a planning submission (Battle and McCarthy II-III).

The steps of conducting a computational fluid dynamics analysis for buildings are explained below. The first step of such analysis is to break down the particular building volume into hundreds of thousands of geometric cells, which make up a three-dimensional mesh or grid. Boundary conditions must be incorporated into the mesh, including flow rates, air temperature, and the location of supplies and exhaust grilles. After the boundary conditions have been entered, equations for heat, mass, and energy are solved at every cell in the mesh. The result is an incomprehensible volume of numbers and it can effectively be understood by the dynamic displays mentioned before.

Nevertheless, like all the other types of simulation, computational fluid dynamics analysis cannot be said to save architects money. The skills required to perform an accurate computational fluid dynamics analysis remain challenging; the computer power needed is considerable, and the costs are high. For architects, the pay off is in smaller, more energy-efficient mechanical systems. Computational fluid dynamics encourages innovation in mechanical design, while lowering margin of error. Sullivan claims that widespread use of computational fluid dynamics in Europe has encouraged more efficient climate control techniques, such as displacement ventilation, radiant cooling, and natural ventilation (Sullivan, Modeling 164).

2.2.4.2 Mechanical Dynamics

The idea of detailed physical modeling of assemblies by describing solids and the interfaces between them can be developed by introducing laws of dynamics into motion simulation. In this sort of simulation, solids have mass and elastic properties; initial conditions of position, velocity, and acceleration are specified; and the laws of dynamics are used to work out physically possible sequences of events. Dynamic simulations of mechanisms provide the basis for static and dynamic structural analysis of assemblies that are not mechanisms like building structures (Mitchell and McCullough 285-86).

2.2.4.3 Human Modeling

The interest and development of digital humans have increased in the last decade (B. Robertson 33). Digital humans are computer-generated, graphically displayed entities that represent either imaginary characters or real humans. The former commonly referred to as “avatars” are used primarily in the entertainment industry. The other digital humans are potentially valuable for architectural design. They are used to test the fit, reach, and motions of people in vehicles and environments. They also permit assessment of movement patterns of individuals and groups of people (Miller 24).

The growth in the interest and development of digital humans can be due to two major factors. First, the advances in computer graphics technology have provided the performance and speed necessary to efficiently duplicate and visualize human motion. Second, design professionals are becoming increasingly aware that human factor is a critical design element that must be accounted for in every phase of the product life cycle (Miller 26).

In one sense, modeling humans is a special case of mechanical dynamics. Digital humans incorporate restrictions on limb and joint movements, and may be scaled for different body types and sizes (Richards 283). Nevertheless, the scope of human modeling can be increased to include not only the laws of dynamics but also other dynamic factors peculiar to humans. Thalmann identifies two main approaches to three-dimensional computer animation and its evolution. The first approach corresponds to an extension of traditional animation methods. The animator uses the computer to assist him in the creation of keyframes and simple motions and deformations like stretching. The second approach corresponds to simulation methods based on laws of physics, physiology or even psychology. Traditional methods allow us to create three-dimensional characters with exaggerated movements while simulation methods are used to try to model a human behavior accurately. The second type of animation is called behavioral animation. (Thalmann 183-84)

Capucci mentions two important factors that should be considered in the development of human models. One of them is the high computer power needed to represent complex shapes, textures, and materials. This is a technological problem and by the development of technology, it is disappearing as mentioned before. The other problem, which exists in all types of modeling, is the issue of true modeling. In order to improve human models and search for more adequate ones to describe humans better knowledge of both the phenomenal reality and our way of perceiving it have to be researched (Capucci 101).

Several major industries have embraced human modeling and simulation. Among the first to apply the technology were the aerospace, automotive, and shipbuilding industries. These industries can be characterized by long product development cycles, high-cost start ups, and intense manual labor demands. Digital humans have been used for cockpit design, aircraft crew cabin layout and instrumentation evaluation, automobile seat and passenger comfort studies, and space station construction planning (Richards 284). In architectural design, although their use is not as widespread as other industries, such models are used in interior design, layout of rooms and office spaces and design of furniture (Krupa 85).

CHAPTER 3. VIRTUAL ENVIRONMENTS AND ARCHITECTURAL DESIGN

3.1 An Overview of Virtual Reality

3.1.1 Definition

Virtual reality is a topic that has been discussed widely in 1990s. Although the interest and developments in virtual reality have only increased, there is not any common definition of it. Several pioneers and groups involved in virtual reality research have developed their own views of virtual reality. Analyzing the related literature, three concepts appear as to be fundamental to the definition of virtual reality: simulation, interaction, and immersion. In this section these concepts are analyzed in relation to the different definitions of the term in the literature.

3.1.1.1 Simulation

The ability to produce real-time interactive simulation is a unique attribute of the computer. In fact, by this ability computer becomes an unprecedented medium. Ivan Sutherland in his famous paper "The Ultimate Display" emphasized this property of computer graphics. He wrote that "The screen is a window through which we see a virtual world. The challenge is to make that world seem real and to make it behave as if it were real" (Sutherland in Garassini 77).

The idea of real-time interactive simulation dates back to military flight simulators. These devices have been used to train pilots without endangering the pilot and aircraft since the early days of flying. The advent of computer graphics made the inclusion of visual feedback possible in the simulator. In such simulations views are generated by computers so that the display instantly responds to the trainee pilot's cockpit controls. Computer graphics used in such systems have a high degree of realism. The realism of simulations applies to sound as well. Spatially synthesized sound systems control every point of digital acoustic space.

In recent years the use of virtual reality as simulation has increased. Visual simulations are programmed for complex scientific research; for training purposes, as in flight or driving simulators; for entertainment, education or architectural design (Cotton and Oliver 184). These applications are covered in detail in 4.1.

3.1.1.2 Interaction

Virtual reality, in one sense, is considered to be any electronic representation that can be interacted. For example, to clean up a computer desktop, a graphic representation of a trashcan is seen on the computer screen, mouse is used to drag an unwanted file down to the trashcan to dump it. The trashcan is an icon for a deletion program, but it is used as a "virtual" trashcan. What makes the trashcan different from cartoons or photos on TV is the interaction it provides. The virtual trashcan does not have to fool the eye to be virtual. In this view of virtual reality, interaction is more fundamental to the definition of virtual reality than illusion (Heim 110).

Virtual reality is usually characterized by a real time interaction. For example, The Dictionary of Computer Graphics gives three definitions of virtual reality each emphasizing the term interaction. According to this dictionary virtual reality is

1. An electronic simulation in which perspective images are generated in real time from a stored database corresponding to the position and orientation of the head of a user, who observes the images on a head-mounted display.

2. An electronic simulation in which images are generated in real time or near real time from a stored database and displayed in such a way as to facilitate real-time interaction with the database, such as a vehicle simulation with imagery presented for viewing out the windows of the vehicle.

3. Most generally, any electronic simulation or display that suggests the sense of involvement or interaction associated with virtual reality as practiced using head mounted displays (Latham 148).

Defined broadly, the concept of virtual reality has increased its scope to include many aspects of electronic life in recent years. The term is used to define any kind of interactive electronic experience in computer networks. It includes virtual universities where students attend classes on line, visit virtual classrooms, and socialize in virtual cafeterias. The term virtual practice is used for many disciplines, including architecture, to define professional groups working on computer networks usually being physically in remote locations. Marlatt predicts that in future economics, accelerated market conditions, and increasing building sophistication will require architects to work at "virtual firms" specializing in a specific building type and that exist only for the duration of a project (Marlatt 94).

3.1.1.3 Immersion

Many people in the virtual reality industry prefer to focus on a specific hardware and software configuration while defining virtual reality. This is the model set for virtual reality by some pioneers such as Sutherland, Fisher, Furness, and Brooks. According to this view, virtual reality means sensory immersion in a virtual environment. The specific hardware first called virtual reality combines two small three-dimensional stereoscopic optical displays, or "eyephones," a head-tracking device to monitor head movements, and a data glove or hand-held device to add feedback so the user can manipulate objects perceived in the virtual environment. Audio with spatially synthesized acoustics can support the illusion of being immersed in a virtual world (Heim 112).

Such systems, known primarily by their head-mounted displays (HMD) and gloves, were first popularized by Jaron Lanier's VPL (Virtual Programming Language) Incorporated. The HMD cuts off visual and audio sensations from the surrounding world and replaces them with computer-generated sensations. The body moves through virtual space using feedback devices like gloves, foot tread mills, bicycle grips, joy sticks, etc (Bertol and Foell 99-103).

However, this understanding of virtual reality has been considered to be avant-garde and remained in the research laboratories. Probably due to the limitations and shortcomings of this hardware like motion sickness, few systems were delivered to real customers for real applications. Therefore, attention has shifted elsewhere (Rosenblum et al., Reborn 21). The definition of virtual reality has broadened its scope as the term describing the conventional interface to late twentieth century computing. Such interfaces are now almost exclusively graphics driven and increasingly, they include three-dimensional animated graphics augmented by appropriate sound (Batty 253). Hence, today it is common to classify virtual reality as immersive and non-immersive types. (Zampi and Morgan 15).

Walker also views VR as a new type of interface suggesting a taxonomy for five generations of computing (Walker in Zampi and Morgan 20). The table below represents this taxonomy.

Table 1. The Five Generations of Computer Interfaces

The Interface	Properties
The plugboard -the computer as switch board-	The earliest type, capable of performing only a limited set of instructions
The punched card machines	Provided greater data handling, and more complex routines
The keyboard and screen	Commands could be directly input and modified
The menu driven program	User is even closer to the machine, not needing to memorize complex commands and routines
Graphical User Interface (GUI)	The current state of technology, in which a mouse is used to point and click
Virtual reality	The next level of technology that provides greatest interaction between the computer and user

The term virtual reality was coined by Jaron Lanier. The designation is, from any viewpoint, a contradiction in terms. The contradiction between the two words is evident; reality cannot be defined as virtual from an existential perspective because virtuality denotes the opposite. Nevertheless, the term expresses the fact that "virtual reality" is not about illusion but rather is about the creation and physical expression of an imaginary world, created and controlled by the user. In spite of the semantic contradiction, the term has become immediately accepted by both the computer community and general public. The other terms such as artificial reality and cyberspace have not been used to embrace all kinds of activities named virtual reality (Bertol and Foell 69).

Artificial reality is a term coined by Myron Krueger, and its scope usually confined within his works. The other term "cyberspace" was coined by William Gibson in his famous book <u>Neuromancer</u>. This term attracted many people with its fictional content. However, it has more or less remained its first scope and never used for scientific works. The expression "virtual environment" is being increasingly used instead of "virtual reality." This term, that has a more semantically correct meaning, probably has been coined at NASA Ames Research Center, in preference to the oxymoronic "virtual reality" (Latham 147). In the scope of this thesis the expression virtual reality denotes the technology involved, while the creative contents and specific applications utilize the terms virtual worlds or environments.

3.1.2 A Brief History of Virtual Reality

Many authors date back the history of virtual reality to the developmental work of Ivan Sutherland at the University of Utah. In 1965, he presented a vision of virtual environments, in the paper titled "The Ultimate Display," that continues to inspire many researchers. His vision was influenced by the introduction of computer-driven display technology (Weimer 246).

Sutherland's aim was to place an observer in the midst of a dynamic computer-generated graphic space and, furthermore, allow the observer to move around and within this real-time perception. In 1968, the first head-mounted display system was reported by Sutherland. His solution was to mount two miniature cathode ray tubes in a headpiece, one positioned in front of each eye. The device was linked to a computer by three aerials that conveyed coordinates locating the position of the wearer's head and direction of view. The display processor instantaneously provided the correct image. The displayed image was a transparent wireframe structure (Porter 138-39). Sutherland's prototype, although crude and cumbersome, led to many achievements in VR. The early works in VR were in three major areas: art, flight simulation and robotics, and military and space-related research (Schroeder 388).

In art, Myron Krueger was the front-runner in exploring the potential of VR-like interactive computing devices. In the early 1970s, Krueger created a gallery installation that allowed users to interact with a two-dimensional computer-generated environment. The main difference between Krueger's approach, called "Artificial Realities," and immersive VR systems is that he did not attempt to create a simulation which gives the person the impression of bodily presence in the virtual environment. Instead, Krueger's system allows participants to interact with silhouette images projected on a wall-sized screen by simply moving in front of these worlds. The system achieves interactivity by recording the user's movements with video camera so that the user's silhouette image can interact with the projected image. This system could also allow multiple users to interact with each other in projection. Krueger claimed to bring a model of interactivity that has not been applied to architecture before. He called his later works as "responsive environs" and "interactive buildings" and emphasized the opportunity of conceiving buildings as defining environments that are "playfully alive" rather than as sterile objects (Krueger 273-83)

In 1980s VR was popularized with Jaron Lanier who came from a completely different background of computer games. At that time, there was an increase in the ongoing research mainly due to the increase in affordable computing power. Computing power is especially required for generating the necessary computer images to create realistic three-dimensional representation. The conceptual groundwork had been laid much earlier by Sutherland, however it was only during the 1980s that the technical means became available to produce working systems that were more than prototypes (Schroeder 390).

The early 1990s saw significant growth in both the number of VR researchers and the research quality, driven by decreasing costs for needed computational and peripheral equipment. At the same period the concept of VR entered common currency. In the popular media it was exploited and trivialized. Due to the fiction-like articles and the movies such as "Lawnmower Man" and "Johnny Mnemonic," the public and research sponsors developed entirely unrealistic expectations of the possibilities and time scale for progress. Many advances occurred on different fronts, but they rarely synthesized into full-scale systems. Then, the excitement turned into unrealizable "hype" (Rosenblum et al., Reborn 21). Besides unrealistic expectations, implementation of the VR vision has been hampered in several other ways such as technology limitations, lack of understanding of human factors, and lack of experience in creating and using new three-dimensional paradigms (Rosenblum et al., Unbound 19).

In spite of all the problems faced in VR research, there is still much ongoing research, probably because of the powerful vision underlying. Rosenblum et al. claim that the next decade will see extensive growth in VR, a process already beginning. Then, he mentions four factors that driving this growth: decreasing costs; developing software architectures that can be used by system builders keeping them from having to reinvent the wheel and relearn old mistakes; confluence caused from more interdisciplinary teams capable of combining the separate advances; and finally the increase in fielded systems that enables field tests for research projects (Rosenblum et al., Reborn 22-23).

3.1.3 Types of VR Systems

A major distinction of VR systems is the way they interface to the user. According to this distinction five general VR system types are described in this section: screen-based VR, immersive systems, video mapping, telepresence, and augmented reality.

Screen-based VR systems use a conventional computer monitor to display the virtual environment. This is also called desktop VR or a Window on a World (WoW). Screen-based VR systems are the most widely used type of VR systems mainly due to the low costs. In the second half of the 1990s, high end PCs have begun offering near-workstation performance at a fraction of cost and many VR software companies have been focusing their efforts on the PC-based products. Such systems are mainly used for presentation purposes. With the emergence of Virtual Reality Modeling Language (VRML) their use has increased (See 3.2.2.1) (Mahoney, PC 53).

Immersive VR systems are often equipped with a Head Mounted Display. This is a helmet or a facemask that holds the visual and auditory displays. The helmet may be free ranging, tethered, or it might be attached to some sort of a boom armature. Projection-based VR systems display three-dimensional images on video projection screens or monitors; users wear lightweight stereo glasses to view them. Some immersive systems project images directly into the both of the user's eyes (HITL, VRD 2). Each image is created from a slightly different viewpoint to create a three-dimensional view. There are several research projects to utilize immersive design environments as media for early stages of architectural design (See 3.2.2.3)

Video mapping is a very specific type of VR system developed by Myron Krueger. This system merges a video input of the user's silhouette with a two-dimensional computer graphics. The user watches a monitor that shows his body's interaction with the virtual world. This type of VR is explained in 3.1.2.

Telepresence is the process through which a participant is allowed to view and interact with a remote location using cameras and other communication devices. Telepresence may involve different types of environments and tasks, from robotic control to simple video conferencing. It is often used for human control of activities in inaccessible or dangerous places such as in fire fighting and surgery. Telepresence applications, except video conferencing, are not much used for architectural design (Bertol and Foell 73-74).

In *augmented reality* systems computer generated images are merged with the user's view of the real world. Instead of creating representations whose perception replaces that of the real world, an augmented reality application complements the real world perception with information not ordinarily discernible by human senses. The actual and virtual worlds coexist in the participant's perceptions as a tool to improve the participant's understanding of her environment. There are some research projects to use augmented reality for architectural construction (Webster et al. 109).

3.1.4 Virtual Reality Modeling Language (VRML)

Virtual environments are expanded to web by the development of VRML (Virtual Reality Modeling Language) in 1994. VRML, both a language and a file format for describing three-dimensional worlds and objects brought the ability to render complicated three-dimensional images in web utilizing simple instructions. Like HTML, VRML is designed to be platform-independent and extensible. Although VRML was developed to be independent of HTML, it depends on the same protocols used to transfer files across the Internet. VRML documents are accessible using a VRML browser. The main advantage of VRML is that powerful and expensive workstations are no longer needed to create virtual worlds. With VRML complex virtual environments can be created with a PC, using text-based instructions. A VRML world is a model of a three-dimensional space, which can contain three-dimensional objects, lights and backgrounds. Objects are built from solid shapes and text, or from primitive points, lines and faces. Material properties and textures may be applied to the objects. In the latest versions of VRML, behaviors can be added to the objects through scripting. In this way VRML enables simulations and walk-throughs of devices and buildings (Heller 19-20).

Von Schweber and Von Schweber predict that in near future design, engineering, manufacturing, marketing and sales will work together on the same media using real-time three-dimensional visualization via the Internet. VRML will enable customization applications, leading consumers to be their own producers and built three-dimensional worlds in the three-dimensional market place. Shoppers in Europe can already browse furniture and interior design elements on the web using VRML, then change attributes such as finish, fabric, color, dimensions, etc. (Von Schweber and Von Schweber 157).

3.2 Architectural Design and Virtual Environments

3.2.1 Virtual Environments as the Ultimate Digital Media for Architectural Design

Virtual reality represents the ultimate development in the process of digitalization of architectural design, which initially started with CAAD. Virtual reality can be envisioned as an extension of computer-generated three-dimensional models. The database comprising three-dimensional computer-generated models is the base for any further rendering and can be utilized by several different applications such as rendering and animation. CAAD models grow into virtual environments in the following order.

Static perspective renderings, from wireframe models to textured surface renderings

↓

Animated noninteractive walk-throughs

↓

Interactive screen-based virtual environments

↓

Immersive virtual environments

It can easily be observed that the characteristics of VR, three-dimensionality and immersion, interaction, and simulation find correspondence in architecture. Architectural artifacts are by their own nature three-dimensional and immersive; in contrast to sculptures or other three-dimensional objects that can be perceived and manipulated from their outside, architectural designs can be inhabited and walked through on its inside. The natural physical immersion of architecture can be rendered at its best in immersive virtual environments. This property is an invaluable help to experience architecture that may find many useful applications. For example, may be one day house-buyers will inhabit virtual model of their prospective houses one week before purchasing.

Another advantage of immersion can be realized by designing in an immersive virtual environment (See 3.2.2.3 for examples of applications). Immersive design can be defined as the act of designing in a virtual environment, where the designer is inside her design. Within an immersive design environment the creation of space becomes possible without any intermediation. Traditional compositional rules, such as symmetry and central organizations that are usually implemented in two-dimensional representations, assume different values when implemented in a three-dimensional immersive environment. The 1:1 scale of the immersive design environment gives the ability to perceive the designed space without the false assumptions that often accompany two-dimensional representations. Furthermore, since the perception of architecture is dynamic, the best aesthetic judgment of an architectural space is provided by the change of perspectives giving a succession of views (Bertol and Foell 115-17).

Interactivity is proposed as an essential characteristic of design media at the early stages of design development by many authors (Campbell and Wells 2; De Vries and Achten 5). Interaction refers to the cognitive aspect of the design process. At the earlier phases of design, architects deal with recursive sketching. Many ideas are generated and tested in a fast manner at this stage. Often the rate can exceed 20 drawings per hour (McCall et al. in De Vries and Achten 5). While sketching architects interact with their designs by re-forming representations. However, traditionally most CAAD packages are not intuitive enough to the designer's thought process to support rapid development of design ideas. Fortunately, virtual reality has great potential for enhancing the way architects interact with their digital models since, it provides a natural interface for design by real time feedback and more intuitive design actions (Smets et al. 197-98; Campbell and Wells 2).

As mentioned several times in this thesis simulation and visualization of design performance are very useful for architectural design. Simulation enables representation of many aspects of design and visualization presents non-visual information in a visual manner to provide feedback. In recent years, taking cues from other parts of society, architects have begun to reinterpret the computer as a tool for processing and communicating information about buildings. In fact, in CAAD the attention has shifted from mechanization of design process to the simulation of buildings with the whole life cycles. The goal of the architect is not to compress the time required to produce traditional documentation, but to explode the amount and nature of information available about a designed building, to the benefit of the building's designers, users and owners (Bojar 91). Virtual environments offer several possibilities for the simulation of designs. These issues are covered in detail in Chapter 4.

De Vries and Achten compare VR-based design systems with conventional CAAD and claim that although VR technology is relatively young and there is no established standard of VR-based design systems, VR technology promises good performance in the early design stage. Because, it provides interaction and simulation that are crucial at that stage of design development. CAAD tools offer good visualization of the design but very poor natural interaction with the user. CAAD does not feature immersion and simulation. On the other hand, VR technology is not suitable for production of the traditional documents used for information exchange and CAAD technology shows the best performance in the final design stage, using two-dimensional representations. Therefore, VR-based design systems should be designed to be used at the earlier design phases and at the documentation phase conventional CAAD should be used (De Vries and Achten 5-8).

To sum up, it can be said that the previous domain of trainee astronauts and video game designers, i.e. virtual environments, return architects to the full scale design practice used by the ancients but this time reconstructed electronically. Architects can design in three-dimensions by trial and error in a dynamically simulated virtual environment. Virtual environments, in this sense, can be the type of design media that was proposed by Jones in 1970s as mentioned in 2.2.2. Being free of most of the limitations of other design media -most importantly incapability of representing time dimension and that of supporting dynamic simulation- analyzed so far in this thesis, virtual environments have great potential to be yet the ultimate electronic media for architectural design.

3.2.2 Applications of Virtual environments in Architectural Design.

Virtual environments are used in architectural design in various ways. These applications are grouped under five headings: virtual environments as presentation tool, virtual environments as aid to digital reconstruction of buildings, virtual environments as design aid, virtual environments as design product, and virtual environments as a tool for simulation and evaluation.

3.2.2.1 Virtual Environments as Presentation Tool for Architectural Design

The use of virtual environments as a presentation tool comprises the majority of architectural applications. Virtual reality representations are well suited to the visual evaluation of alternative designs, since they allow viewing a design from any angle and position. The observer can take imaginary walks through the designed building in a much more intuitive way than other digital representations. Walk-throughs can become quite sophisticated if the interaction and control devices include voice commands, audio, and a haptic system allowing not only the ability to see but also to touch walls and furniture. Very realistic simulations can be achieved when photographs of the building sites are combined with the computer-generated design, in an augmented reality type of experience.

Moreover, architectural virtual reality applications allow the user to become actively involved in the design process. The user can make changes of colors, textures, materials, lighting, furniture, etc. Therefore, virtual environments provide effective designer-client communication and they are used as marketing tools by many architectural offices.

In United States, residential home builders use virtual reality model homes for display at real estate sales centers in the place of model homes. Commercial developers use virtual reality for tenant fit-outs in office buildings or retail spaces. Product manufacturers also use VR applications to display at trade shows or retail centers. Interior designers and merchandisers use VR applications to help their clients visualize how they will decorate and furnish spaces. Similarly, using the virtual reality modeling language (VRML), some architectural offices place buildings on the Internet to help clients market their projects. These VRML files can be downloaded from the Internet onto home computers. Potential buyers or tenants can experience these spaces by using navigational controls provided by VRML-supported World Wide Web browsers found free on the internet (Neil 53).

Although major VR facilities still cost much, even the smallest firms can produce web- and CD-ROM-based VR presentations. On the other hand, firms with larger budgets can rent theater-like facilities to present their three-dimensional walk-throughs to small audiences. The return on the investment comes as clients make comprehensive decisions as a result of thoroughly understanding of the building designs. A navigation can reveal many design problems that would not be detected from static renderings. By walking through an unbuilt design, the spatial feeling of the rooms and the proportions of different architectural elements can be experienced. Using these tools at the beginning of the project can save many costly changes late in the design process (Mays, Making 163).

3.2.2.2 Virtual Environments as Aid to Digital Reconstruction of Buildings

Another valuable application of VR is in the reconstruction of important buildings and sites that are difficult to access. These may be historic buildings, archeological sites, museums or popular science centers. The experience of visiting these virtual buildings is interactive and self-directed (Kirk 63). The most outstanding presentation of VR reconstruction is offered by a series of conferences called "Virtual Heritage" that took place for the fist time in 1995. The United Nations Educational, Scientific and Cultural Organization (UNESCO) World Heritage Program supports the use of VR in world heritage applications. The recent virtual world heritage projects are widely spread across the globe from the virtual Stonehenge to Giza pyramids and from Macedonian churches to Chinese palaces (Fisher and Fraser 16-17). The Italian company Infobyte develops VR projects focused on the reconstruction of monuments and sites. One of their VR project, called "St. Peter's Basilicas," combines models of the current church with the earlier basilica, both demolished in the sixteenth century. The project points out the effectiveness of VR in the study of historical layering of sites and monuments (Fakespace, 3-4).

3.2.2.3 Virtual Environments as Design Aid

The potential of VR as design aid is increasingly being explored by researchers. Virtual environments offer several possibilities to be utilized as design media, so that some researchers began to discuss "Virtual Reality Aided Design (VRAD)" instead of CAAD (Regenbrecht and Donath, 155).

However, due to the relative recentness of VR technology and complexity of design process, applications of VR as aid to architectural design is still at an experimental stage. It should be emphasized that most of the experimental projects are proposed to support conceptual design stage. The main reason for this is that VR technology is accepted most promising at this stage of design development due to the interactive and intuitive interface provided. The other reason is a technological one, because of the limitations of VR hardware and computing power, the models that can be created within these systems tend to be rough and imprecise. The main idea for such systems is to sketch a design idea in three dimensions. Therefore, at the current state of development VR-based design systems do not claim to replace CAAD packages but search for the new possibilities for architects. Moreover, most of these experimental systems utilize CAAD features like pull-down menus for the design operations and mouse as control device (although these are three-dimensional). It can be said that VR-based design systems tend to mimic conventional CAAD just like early CAAD packages had mimicked traditional design media. In this section some experimental works designed to utilize immersive virtual environments as design media are covered. The examples are not aimed to be exhaustive, only the most outstanding projects are mentioned.

The Blocksmith project conducted at the Community and Environmental Design and Simulation Laboratory (CEDeS Lab) of Washington University aims to provide software tools to facilitate immersive conceptual design. The system allows designers to create simple objects and modify existing objects in virtual environments. Blocksmith project uses similar data topology (point, line, plane, volume) and design operations (copy, cut, paste, snap, etc.) to CAAD programs. While the software is being used only for research and educational purposes, the CEDeS Lab predicts that the project can eventually aid in the development of commercial software packages that enable architects to design real-time in virtual environments (Campbell and Davidson 207-8).

Conceptual Design Space (CDS) project of Georgia Institute of Technology is another fully immersive real-time virtual environment designed to be used at the early stages of design. The CDS system combines functionality of any walkthrough package with modification and creation functionality. The models created in CAAD packages can be modified (translate, rotate, scale, change, etc.) and simple building units can also be created (Bowman 1).

Voxdesign is another VR-based design system developed at Bauhaus University, Weimar, Germany. Voxdesign aims to provide an immersive environment supporting a one-to-one experience for the user. Through the use of a physical environment called platform the free interaction space in the real world is provided. Voxdesign utilize voxels as units to produce design. The user builds architectural space by placing and modifying voxels. Color, texture and audio are also used. The research team reports that although there are some problems like computation speed, motion sickness, etc. the system is promising to be used for architectural design and design education (Regenbrecht and Donath 157-68).

3.2.2.4 Virtual Environments as Design Product

In general there may be two broad application categories for virtual environments in architectural design. One of them, that is discussed so far in this thesis, is the use of virtual environments to produce better built-architecture. The other type of application that attracts many designers is to design virtual environments as a final product. The unprecedented growth of the on-line culture has led to a desire and demand for three-dimensional content experienced trough three-dimensional (even virtual by the help of the VRML) interfaces. This three-dimensional content needs to be consciously designed and constructed (Benedikt in Campbell and Davidson 221).

Architects as three-dimensional designers are being called to answer this challenge. Architects, since they are educated in three-dimensional design, have an advantage over computer illustrators in creating realistic spatial environments and are quickly moving into multimedia markets. In the United

States several architectural firms offer this type of digital design service (Sullivan, Multimedia 121). Since there is no constraints (physical constraints like gravity, or legal constraints like building codes) in virtual environments, architects feel more freedom while designing such environments. This area of design has developed so fast that some architects declared the birth of a new design profession: virtual architecture. They claim that in time virtual designers will be educated side-by-side with the designers of physical buildings learning to design three-dimensional space in studio setting. Their technological education (equivalent of "construction") will be that of computer science and programming (Campbell and Davidson 218).

Inevitably, such developments have affected architectural praxis. Some architects, mostly the academicians, attempt to use abstract potential of virtual environments to produce physical buildings or "hybrid" structures. The most well-known of them is Marcos Novak and his team at the University of Texas at Austin. Novak named three kinds of future architecture: liquid spaces, transarchitecture, and avatarchitecture. He proposed long theoretical justifications for these fantastically named works of architecture. However, for all their aspirations of creating a space that breaks the boundaries between the real and the virtual, these architectural studies only exist mainly in the computer (Betsky 88-94)

CHAPTER 4. DYNAMIC SIMULATION IN VIRTUAL ENVIRONMENTS AS AN EVALUATION TOOL FOR ARCHITECTURAL DESIGN

4.1 Applications in Other Fields

Research in VR has shifted from the technology to the content of virtual environments in the second half of the 1990s and parallel to the development of VR technology and available computational resources, the use of virtual environments for utilitarian purposes have rapidly increased (Sherman 473). In this part of the thesis applications of simulation and modeling in virtual environments are discussed under three headings: virtual prototyping and manufacturing process simulation, training, and visualization.

4.1.1 Applications in Engineering Design: Virtual Prototyping and Manufacturing process Simulation

Although the idea of using VR in industry is not a new one, VR technology has only recently matured enough to enable engineering design applications. Several companies and government agencies are currently investigating the application of VR techniques to their design and manufacturing processes. Virtual prototypes of product designs are replacing the real ones. Virtual prototypes can be defined as dynamic, interactive, often immersive three-dimensional CAD models utilizing VR technology and developed to analyze product designs. Such computer-based models are usually referred as to be "intelligent" and they capture product content, generate and simulate manufacturing processes, and predict product behavior. When once built, a virtual prototype can be used to support diverse activities such as cost estimation, marketing, and material-requirements planning throughout the product's life cycle (Halpern 23).

The most widespread and rewarding use of such virtual prototyping tools occurs at conceptual design. Automotive industry is forerunner for these applications. They use virtual prototypes to eliminate costly physical models at the early stages of the stylistic design process by allowing a series of designs to be produced and distributed in a fast manner among the design professionals (Hodges, Visualization 56).

As the cost of VR systems drops, other applications that once seemed cost-prohibitive are becoming a possibility, for example, simulators that allow service providers to experience the impact of their work on their customers. By studying the results of potential customers' interaction with a virtual prototype designers can understand the advantages and disadvantages of a proposed design. For example, automotive industry uses virtual models to evaluate interior design of automobiles. For such an evaluation, automobile designers sit in a stripped-down car interior consisting of a seat, a steering wheel, and pedals. This physical model is calibrated to the fully designed virtual model of the car's interior. When a designer is evaluating a virtual prototype, the display tracks the designer's head motion as she looks around, and the visualization is updated in real time. Accessibility is tested through the use of a hand –tracking mechanism. Force feedback and haptics can also be utilized in such evaluations (Mahoney, Chrysler 61-62). Another advantage of virtual prototypes is explaining concepts and ideas to non-technical persons. Designers usually have difficulty in this process. Three-dimensionality and interactivity of virtual prototypes help designers in explaining design ideas to the others (Harding 20)

The other industrial application of simulation and modeling in virtual environments is the simulation of plant layout and manufacturing. Plant simulation in virtual environments makes it possible to evaluate material flow, analyze manufacturing and assembly processes, and optimize the entire production process. In a simulated manufacturing environment bottlenecks can be eliminated by trying out several "what if" scenarios (Boyd 46).

Increases in computational power and control methods enable the creation of three-dimensional virtual humans for real-time interactive applications (Earnshaw et al. 20). The issues related to human factor in a product's design can be explored by the help of virtual humans. Such simulations provide insight into a product's usability, and help to determine the optimal placement of components based on the information (Mahoney, Prototyping 39). Virtual humans can also be added to the virtual manufacturing environments. Humans are modeled in terms of their interactions with machines considering such things as arm's reach, posture and caloric use when performing production activities. In addition, researchers are currently investigating ways of having virtual humans perform complex tasks reliably (Earnshaw et al. 20).

Schulz et al. explain that stereoscopic viewing proved its value in all simulated environments for engineering applications. Nevertheless, a fully immersion is not needed for most of the applications. VRML files at low-cost workstations and PCs can effectively be used for documentation and communication of engineering concepts (Schulz et al. 48).

4.1.2 Applications in Training

Simulation in virtual environments is used for training purposes in many areas: industry (Greengard, 1998), medicine (Mahoney, Simulating 1997); or other work areas involving high risk like fire fighting (Tate et. al., 1997), truck driving (Mahoney, Defensive 1997), etc. According to the advocates of training in virtual environments, trainees could learn by performing in environments nearly identical to actual ones using VR simulations. Virtual reality simulations are most valuable in training where "hands-on" practice is essential but actual equipment cannot often be used –either because it is too expensive, too dangerous, too susceptible to damage, or simply unavailable at training sites.

For training purposes VR systems mostly do not need to be immersive. Therefore, PC-based non-immersive VR systems are increasingly used for training. Immersive virtual environments are used to simulate medical case studies like emergencies (Mahoney, Simulating 95). By the help of such systems physicians "walk in the shoes" of their patients and oncologists may understand the fatigue felt by chemotherapy patients. Hodges claims that if technology enhancements continue, nonimmersive VR training systems will become common in training programs in the next few years (Hodges, Training 58).

4.1.3 Applications in Visualization

Visualization is the use of computer graphics to create visual images that aid in the understanding of complex numerical representations of concepts or results. Such numerical representations may be the output of numerical simulations, as in computational fluid dynamics (CFD) or molecular modeling; recorded data as in geological or astronomical applications; or constructed shapes, as in visualization of topological arguments.

Visualizing data provides new understanding of data sets because it can help to identify patterns that are not otherwise apparent. These simulations often contain multi-dimensional data in a three-dimensional volume. VR systems are very helpful in the unambiguous display of these data structures by providing spatial and depth cues. Moreover, VR interfaces allow rapid and intuitive exploration of the volume containing the data. In a virtual environment, objects representing data can be directly manipulated. For example, a user can physically reach out and grab an object that is creating traces through a velocity field and move it to a new location. Otherwise, this must be done using complex user-interaction techniques. Visualization in virtual environments is already feasible with the current technology, since visualization is oriented toward the informative display of abstract quantities and concepts, rather than realistically representing objects in the real world (Bryson 62-64).

Visualization of simulation results find many applications in engineering design. For example, the latest generation of acoustic simulation tools enable designers visualize the propagation of noise and vibration throughout a proposed design. Such visualizations are very useful for determining how changes in one design variable will affect others, and they reduce costs and cycle times. Moreover, they can also be effective tools for discovering phenomena that physical testing may not reveal; since, they increase the user's level of understanding of simulation results (Deitz 65-66).

4.2 Applications in Architectural Design

Theoretically, anything can be simulated in a virtual environment. Donald Greenberg, one of the computer graphics pioneers, predicts that if the progress in computer graphics and hardware technology continue as of today, near the end of 2025 the display and computational capability to produce images that are both physically accurate and perceptually indistinguishable from real world scenes will be available. This means that at that time simulation technology will reach such a level of capability that there will be no difference with real and virtual worlds and verification tools might be needed to avoid confusion between them (Greenberg, Outlook 36). Therefore, we suggest that dynamic simulations in VEs can be produced for the each component of the life cycle of a building from the decision about designing the building to its demolition.

Although there is no limit for the application areas of dynamic simulations in virtual environments for architectural design, at the current state of simulation technology two areas seem especially promising for near future: evaluation of human factors issues and visualization of environmental factors.

4.2.1 Evaluation of User-building Interaction

Any type of design should be considered as an interface between people and physical things (products, buildings, etc.) and each work of design has to respect the user needs to be regarded successful. Jones argues that designs should be based on the dynamic and experiential user needs. He calls this user responsive way of designing as "process-based design" and contrasts it with "product-based design" that is static and object-dependent (Jones in C. Mitchell 61). However, the information needed for user responsive design is fragmentary, imprecise, and highly subjective. Even if reliable information existed, it is not so easy for it to be used for design purposes (Iwaki 124). Fortunately, new developments in computer technology leads to a new generation of user responsive designs focusing on the dynamic experience of users, not on the product itself (C. Mitchell 62). Companies are increasingly trying to develop products that are more responsive to the users. For example, in Japan "humanware" products are evolved by interdisciplinary product planning teams that concentrate on adapting products to the life style of their users (Iwaki 130). It is obvious that architects can benefit from these developments to produce buildings that are better adapted to their users. In this part of the thesis the opportunities for architects to evaluate user-building interaction in VEs are discussed and some already realized examples are also mentioned.

As discussed earlier in this thesis, human modeling software has already reached a level of maturity to be used in design testing applications. By combining the virtual model of her design with virtual humans, an architect can understand the possible results of interaction between the proposed building and its prospective users. At a very simple level, accessibility, and safety considerations can be analyzed according to the different user types (female, male, elderly, children, disabled, etc.) Using specially designed software architects can be immersed in their designs "becoming" the actual user. Simple levels of this operation are already possible with the current technology. Although Transom Jack and Division's dV/Manikin are first to use motion-captured input data, most human-modeling software packages are now adding the ability to puppet a virtual human with data captured from real people (B. Robertson 36). Transom Jack is the human factors and ergonomics visualization software that has gained the most recognition and use in the U.S. Jack was produced in 1982 by Norman Badler and his team, when NASA contracted the University of Pennsylvania's Technology Transfer Center to develop detailed computer models of humans. NASA's Flight Crew Support Division, The Army Research Office and Army Human Engineering Laboratory supplied the university with human factors research. Jack can be used for architectural and interior design applications to test the building designs against an average user (Krupa 84-85). However, users can be extremely diverse for the buildings and it will be a real challenge for architects to simulate people with unusual properties. For example, an architect designing a house for an elder person with glaucoma (an eye disability for elderly) will really benefit from seeing the virtual model of the building "through the eyes" of her client.

A similar possibility has been recently realized for the wheelchair users. Ohio State University's Rehabilitation Engineering Center for the Quantification of Physical Performance conducted a research for the determination of environmental accessibility and wheelchair user proficiency through virtual simulation. They developed a virtual-structure prototyping system that allows navigation by a person using a power wheelchair. The system consists of an instrumented, joystick-driven power wheelchair connected to a high performance graphics workstation. The system simulates the actual speed and maneuverability of the particular wheelchair within a virtual structure. The display generates realistic interiors containing multiple light sources and surface textures and is viewed in stereo through lightweight polarized glasses. Collisions between the virtual wheelchair and the environment are detected by a hierarchical data structure. Although the aim of the system is not only architectural applications, the developers mention architects as prospective users of the system to improve the handicapped accessibility of building designs (Stredney 1-3).

Autonomous virtual humans can be used in analyzing the events like evacuation, panic, or wayfinding in buildings. An interesting example to this was realized by Colt virtual reality, a company that makes ventilation systems, in 1994. The company produced a virtual reality simulation model of evacuations for building design. The system is based on a mathematical model initially designed for Britain's defense ministry to simulate how people get in and out of places. The model is applied to people running from burning buildings. The resulting program called virtual-egress analysis and simulation (VEGAS) combined object orientation and virtual reality. VEGAS lets architects create a virtual world in which the way people react to events depends on the individual characteristics allotted to them. This means that in a fire egress simulation everyone follows a different set of rules. The personalities given to virtual humans are drawn from behavioral studies. The mix of personalities can be changed easily. This is very useful because user profiles may change in a building. The program can be run repeatedly with different groups of people, so that designers can find out how their designs work for unexpected cases (for example if there is an unexpectedly large number of wheelchairs in a theatre). With VEGAS the architect can get inside the virtual environment and see it from the viewpoint of the actors. She can check the visibility of exit signs as the smoke spreads and discover what happens if an actor behaves in an unusual manner i.e. runs against the flow, blocks a door etc. (The Economist 84-85)

4.2.2 Visualization of Environmental Factors

Environmental performance of buildings like thermal behavior, structural behavior, acoustics and lighting are important criteria for building design. The computers can currently relatively easily simulate most of these aspects of design. Nevertheless, experiencing design behavior is yet only possible with VR. Conventional simulation tools leave architects with a large amount of data in a difficult to understand format. Mahdavi explains that architects are not willing to use conventional performance simulation tools because of the non-graphical output and uncomfortable interface of such tools. On the other hand, as discussed in 4.1.3 virtual environments have the potential of providing more information in an easily understandable form. VR interfaces can display data in a way much closer to their nature than by means of other symbols such as words and numbers. Design behavior such as thermal insulation, acoustic isolation, structural stress, etc. are represented as colors, sounds, motion-models and so on and these can be directly mapped on the virtual model. Interaction in a three-dimensional space, navigation, and instant feedback are the other benefits of visualization in VEs.

One promising area of visualization in VEs for architectural design is Computational Fluid Dynamics (CFD). As discussed in 2.2.4.1 CFD is used for the simulation of air movements and heat transfer in buildings. An example for visualization of CFD simulation results in VEs was realized by Division for Matsushita Electronic Industries in Japan. In the project a VE is created to simulate the interior of a modern Japanese two-storey house. Wearing a HMD and holding a three-dimensional mouse each room can be explored, turning on and off the lights, running the water in the bathroom; opening and closing the curtains, doors and windows, moving furniture, etc. Since Matsushita's main business is designing air-conditioning and heating systems for domestic market, the virtual house provides them an environment to evaluate new designs. New designs are imported to the display from CAD files without the expense and delay of making a series of full-scale models. Their designers can review how their products would look and could be operated in a typical setting. The program is set to visualize and evaluate air and heat flows. The program also visualizes the light rays projected from the lamps (Zampi and Morgan 110-12).

Another application area of visualization in VEs for architectural design is the visualization of simulation results of a fire in a building. Bukowski and Sequin reports an integrated VR system that creates a simulation-based design environment to evaluate the performance of building designs in case of fire. The program integrates an architectural walkthrough (Berkeley Architectural Walkthrough) with a numerical fire simulator (National Institute of Standards CFAST fire simulator). It provides real-time, intuitive, realistic and scientific visualization of building conditions in a fire hazard situation from the perspective of a person walking through a burning building. The viewer can observe the natural visual effects of flame and smoke and the concentrations of toxic compounds in the air, as well as the temperatures of the atmosphere, walls and floor. Warning and suppression systems such as smoke detectors and sprinkler heads can be observed in action to help determine their effectiveness. The researchers claim that building design evaluation is one application domain for dynamic simulation and visualization in VEs with a particularly high expected pay off and their system is useful for architects who want to evaluate their designs for fire safety (Bukowski and Sequin 35-36).

Auralization of sound in VEs (i.e. rendering spatialized sound based on acoustic modeling) is another application area of visualization in virtual environments for architectural design. A recent spatialized sound VR system developed in the Bell Laboratories computes reverberation paths from a sound source to a listener and visualizes the results. This can be a great help for the architects trying to solve acoustical problems in building designs. Since sound may travel from source to listener via a multitude of reflection, transmission and diffraction paths accurate simulation of sound propagation is not an easy work. Researchers claim that their system realistically and interactively simulates the behavior of sound even in the complex VEs and it supports the evaluation of the paths of reverberation, reflection and diffraction (Funkhouser et al. 21-22).

4.3 Discussion on the Future Use of Dynamic Simulation in Virtual Environments as an Evaluation Tool for Architectural Design

Although the benefits of CAAD tools and techniques are well known in architecture, dynamic simulations in virtual environments are not much used for architectural applications. This is probably due to the fact that architects themselves are not much involved in exploration of the possibilities offered by the computer technology. However, as mentioned several times in this thesis, increased complexity in architectural design processes and clients' ever-growing demands toward results force architects to explore and adapt new technologies. Criteria like environmental performance of buildings and human factors issues should be taken into account, preferably in the early stage of design and not during analysis later in the process. Otherwise, there is always a danger that designs will be more and more based on intuition and aesthetic considerations rather than a realistic understanding of future performance of proposed buildings.

We suggest that in order to meet these demands a virtual model of proposed building, that dynamically simulates all the phases of a building life span from the brief to the demolition, should be produced in an early stage of design development. Such a virtual model can be used for several types of applications from design to marketing and facilities management. We believe that future use of CAAD will be more and more based on simulation of buildings rather than other aspects of CAAD. The main advantage of using computers in architectural design is producing realistic models of a proposed building and its context. The building model should not only look as if it was real, but also it should "behave" as if it was real. A single three-dimensional digital model that includes the behavior of the design elements and simulates a building with its whole life cycle has long been a dream for CAAD researchers. However, the current design media for architectural design, paper-based drawings, physical scale models and conventional CAAD software are very limited compared to the functionality of virtual prototypes used in engineering design (See 4.1.1). The 3D-based object oriented CAAD software mentioned in 2.2.1 is an important step toward realization of this idea for architecture. The next step should be virtually constructing and making use of a building prior to actual construction. With the rapid developments in computer technology this idea once may seemed unrealistic can be realized now. Developments in VR technology and successful applications in engineering design have proved the effectiveness of dynamic simulations in virtual environments. In the following parts of the thesis, first our approach is compared with conventional CAAD, and then development proposals are discussed.

4.3.1 Comparison of Dynamically Simulated Virtual Models with Conventional CAAD

The possible advantages of a three-dimensional, interactive, dynamically simulated virtual model for architectural design compared to conventional CAAD are listed below:

1. Simulation of building performance for the whole life span of a proposed building saves the client and architect time and money and enhances the quality of design. Buildings are expensive entities to build and maintain. The Building Cost Information System (BCIS) of U.K reports that house rebuilding cost index has risen continuously between 1996-1999 (BCIS 1). Besides construction, operating and maintenance costs of buildings also tend to increase. The Building Owners and Managers Association (BOMA) reports that costs of operating buildings and rents per square meter were increased for the office buildings in U.S. in 1998 (BOMA 1-2).

We discuss that the deficiencies in a building design may cost much through the whole building life. Even a small increase in the operating and maintenance costs of buildings per square meter will be totaled much through the years. We claim that many of these deficiencies can be eliminated by dynamic time simulations in virtual environments.

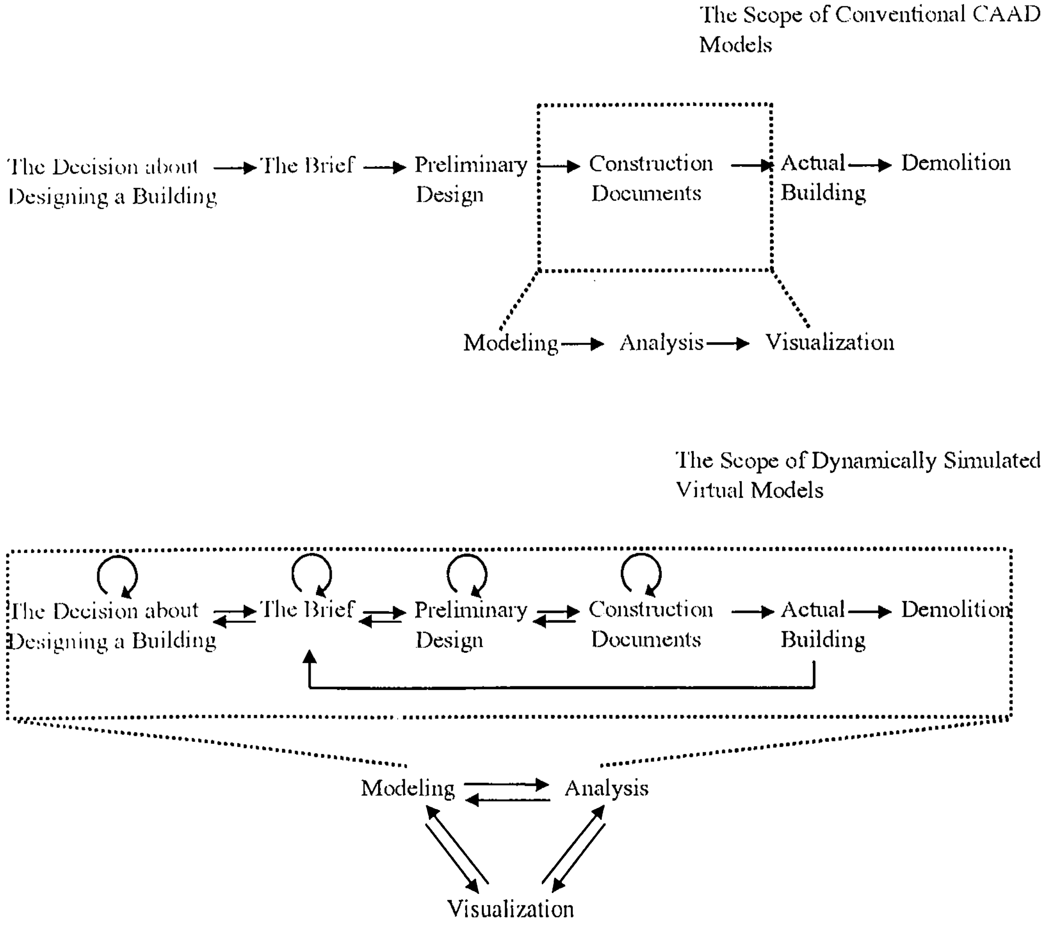
In architectural design, most of the important decisions (orientation, circulation, functional layout, etc.) are made at the early stages of design. Nevertheless, in the related literature it is well documented that most of the CAAD software do not support these stages of design development. CAAD software is traditionally used for producing construction documents after the preliminary design is complete. The digital model produced at this stage is rarely used after the construction of the building. On the other hand, as discussed in 4.1.1 VEs technology has proved itself in the early phases of engineering design.

One may claim that such applications for architecture will cost much, but the rapid decreases in the costs of computer products suggest that they can be feasible even for the smallest offices. Screen-based VR can be used for most of the applications instead of the immersive type and PCs that are widely used in architectural offices may suffice for most of the applications.

2. In conventional CAAD modeling, analysis and visualization processes follow a linear sequence. Analyses are applied after the modeling is complete and visualization occurs at the latest stages of design only for presentation purposes. However, a virtual model is more flexible compared to physical models and other CAAD models. Simulation, evaluation, and modification can take place within seconds through a highly interactive user interface with real time feedback functionality. Therefore, modeling, analysis and visualization

can occur concurrently. The benefits of this property are clear: the shortening of the design cycle and quality improvements due to gained information (See Figure 1).

Figure 1. Comparison of Dynamically Simulated Virtual Models with Conventional CAAD



3. Unlike conventional simulation tools based on texts and two-dimensional charts and tables that are difficult to understand by non-technical persons, virtual environments allow three-dimensional and dynamic visualization of simulation results. This property helps understanding and communicating design ideas by related parties even they are non-technical. The developments in the web-based VEs are promising for the transportation of virtual models.

Through Intranets or the Internet virtual models can be transported to the clients, colleagues, and other technical professionals related to building design.

4.3.2 Conclusions and Suggestions for Further Research

Analyzing the current media of architectural design, we conclude that VR systems and resulting VEs are yet the best media for dynamic simulation of building designs. Although their uses are very promising, production and utilization of dynamic simulations in VEs for architectural design require further study on different fronts.

First of all, we suggest that architects should redesign their design processes according to the new possibilities. They should redefine their expectations from CAAD and its way of use in their professional activities. This can be viewed as an extra work for architects, but in the age of virtual reality most of the professions had to redefine their work processes and architectural design could not be an exception. We discuss that competitive market conditions, increasing life cycle costs of buildings, and clients' demands toward high quality results have been already forcing architects toward such a change.

The other important considerations for the efficient use of dynamic simulations in VEs for architectural design are discussed below.

Compatibility and Standards

Compatibility and standardization have always been problems for the users of CAAD software. Architects usually have to use two or more software packages to produce a high-level output such as a complete animation. Designs are produced with a two-dimensional drafting software, and then an animation or rendering software is used to complete the task. Lack of compatibility between different computer aided design software renders the use of them together impossible. Moreover, integration of evaluation tools with design tools has often been very difficult because of the difference of the internal information representations. VEs will not be an exception to these problems. Since a great deal of data is needed to perform simulations, VEs should allow gathering data from different nodes. In order to read data from different systems, the VR system and the other digital tools of the architect have to be compatible. Market conditions have been already forcing the vendors of CAAD software to produce compatible products, but we suggest that these efforts should also embrace VR systems.

Since VR technology is relatively new, it can be easier to solve these problems at this stage of development. Development of standards for the VEs on the web is an important step toward compatibility and standardization of VEs. Virtual Reality Modeling Language (VRML) is the result of such efforts (See 3.1.4 for more information on VRML). The current version of the language, VRML 97, became an International Organization for Standardization (ISO) standard in 1997 and now forms the basis for many new works (Nadeau 18).

Interface Design

Computer is a tool that can provide several kinds of services, but to benefit from these services users must communicate with the computer system. Therefore, interface design is an important factor for obtaining maximum benefit from the CAAD software. We discuss that most of the conventional CAAD interfaces are difficult to use and waste time and energy. For example, we may compare the mental effort needed to draw a line with a pen on a paper and the mental effort needed to draw a similar line with a conventional CAAD system. The CAAD system requires much attention to activate the "line" command and to specify several parameters. Attention shifts from the design task to interaction task that consumes time and energy. We suggest that a design system should be quick and intuitive, capturing the flow of the concepts as quickly and naturally as possible. Advantages of VR interfaces are mentioned several times in this thesis. In general, it can be said that a virtual model is more adaptive to design processes of architects than any digital model. We believe that VR interfaces can eliminate most of the problems in conventional CAAD interfaces. Nevertheless, to obtain maximum benefits from dynamic simulations in VEs for architectural design, specific needs of this task should also be addressed. For example, what should be the properties of an ideal interface to obtain simulation data from different nodes and to integrate them into the geometric model? Or, how the visualization of simulation results should interface to architects? Since simulation data and resulting visualizations should be shared by the different participants of building process, how a common ground can be provided for different applications? Answers to these and similar questions lie in the interface design research. It is not possible to mention all the related issues in the scope of this thesis, but we believe that these considerations deserve more attention for further work.

The Need for the Collection and Distribution of Information

Any type of computer simulation necessitates information to be gathered. When this information is complex and/or divergent, as in our case, this process can be time-consuming and expensive. Moreover, this data needs to be continuously updated. Interdisciplinary work is needed for most of the instances and we cannot expect that single architectural offices, no matter how large they are, will be willful or capable of conducting these processes. We suggest that the information required for the production of dynamic simulations should be drawn from Environmental Design Research (EDR). EDR has been producing a huge amount of data already that is waiting to be used. Researchers of environmental design often complain that their works do not have impact on the architectural community. We discuss that this not only due to the ignorance of the architects, but it is also due to the inconvenient format of the outputs of EDR for architects. In fact, some architects still do not know what EDR means and they do not have time to learn much in the rapid market conditions. Simulation in virtual environments can effectively utilize research data and present the results in a way familiar to the architects. Architects, as designers working in three-dimensions, will really benefit from the three-dimensional and interactive visualization in VEs.

We also suggest that government agencies, research institutions and professional organizations such as Chamber of Architects in Turkey (a member of The Union of International Architects) should support and fund research and development on this topic. Potential applications of dynamic simulations in VEs are so rapidly evolving that perhaps in near future buildings will be checked against regulations in dynamically simulated VEs.

Simulation in VEs will also help to increase the methodological knowledge in architectural design. As discussed earlier in this thesis, simulation enlarges the insight in the overall system and effects of a certain alteration on one or more variables can be observed easily. Therefore, verification of some design theories can be possible in VEs.

Simulation models and programs can be distributed over the Internet easily. In this way, even the architects having the simplest computer configurations can conduct simulations by connecting to the high performance computers preserving simulation model in a distant place. The simulation data can be marketed over the network, for example, in the form of virtual human profiles derived from behavioral research. In order to preserve the copyrights, several measures can be taken such as presentation of low resolution data at the trial stages.

Validation of Simulation Models and Representations for Visualization

Validation of simulation model is a common step for every type of computer simulation as discussed in 1.3.2. This process is required to ensure that the mathematical model successfully represents the reality. Discussing dynamic simulations in VEs for architectural design, a more philosophical question lies in the "True Model" concept (Şenyapılı and Özgüç, Proposal 178; Şenyapılı, True Model 137-38). Visual experience and perception comes into the scene for this case and certain difficulties in modeling time, colors and textures in relation to the scale factor of physical dimensions should be adressed. Since, it is yet impossible to simulate the real visual experience, it is offered to "catch a likeness" that reveals a key aspect of a prospective design, rather than trying to simulate the whole visual experience (Mark in Şenyapılı, True Model 138).

As discussed in 4.2.2, we believe that more effective visualization of building performance will lead to new insights and more efficient decision-making for architectural designs and the decreasing costs and increasing speed of hardware and software and the developments in the Internet have already rendered visualization a potentially useful and feasible design tool for architects. However, for the effective use of visualization in architectural design some points should be considered.

First of all, we introduce that visualization techniques and representations should be well adapted to the needs of architects. Visualization research originated from the scientific community's efforts to cope with the huge amount of scientific data. Therefore, specific representations have already produced in scientific visualization for the technically skilled audience. Since architects are not scientists, ease of use is a key factor for the efficient architectural visualizations. Visualization designed for architects should enable them to get the information they need on their specific problems, make sense of it, and reach decisions easily in a relatively short time. Interfaces should allow easy manipulation of data and representations should not lead to misinterpretations. Avoidance of misinterpretations is extremely important, since architects tend to regard the results that are obtained from computers as totally correct. If they misunderstand the information, this may cause remarkable faults in their designs.

The lack of standards and ways to integrate visualization across multiple applications (Gershon and Eick 30) renders these tasks difficult. Fortunately, the developments in the Internet is promising for visualization applications. The visualization data can be sent over the network, and visualization can be performed on the architect's side. This not only saves the time required to import the visualization product over the network, but it also lets the architect manipulate the displayed visualization to suit her specific problems or needs. Last but not least, we suggest that since the media of visualization are relatively new, potential benefits of using them need to be well understood. Architects should not use this medium as a replica of paper, but should explore the new possibilities offered.

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