A SYSTEMS DESIGN APPROACH FOR SUSTAINABLE AFFORDABLE HOUSING

by

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ABSTRACT

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Engineers and scientists are continually searching for more efficient methods of resource management which promote sustainable living and the opportunity for a quality way of life for all people. Global increases in population are fueling the demand for housing, especially in developing nations, therefore the desire to provide an affordable house which utilizes resources in an efficient manner is a concern of civil engineers. By approaching the design of a home from a civil engineering systems perspective, considerable resources may be saved and a better quality product can be produced. A sustainable affordable house design is one which minimize cost and environmental impact while maximizing the social acceptability. Multiple design alternatives which assess the true need of the people, utilize appropriate building materials, consider the physical environment, and utilize methods of industrialization, should be synthesized. A multi-objective evaluation procedure may then be used to evaluate the alternatives based on life cycle cost, material life cycle and the functionality and familiarity of the design. The selected preferred alternative should then be optimized by changing individual design parameters, re-evaluating the design and observing the resulting change in system performance.

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I would like to sincerely thank Professor Adrian M. Crawford for his valuable insight and guidance throughout this thesis.

I would also like to thank my family for putting up with me and especially Mara De Giusti for her invaluable research skills and best friendship.

Lessons learned: Hard work pays off and sleep is overrated.

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CHAPTER ONE

INTRODUCTION

Two fundamental rights of all human beings are the right to adequate shelter and the right to live in a clean and healthy environment. An adequate home provides physical protection from the environment as well as financial and social stability via home ownership. A collection of homes can be viewed as a community which collectively manages the surrounding environment and its resources to sustain the lifestyle and personal well being of the community members. Many recent global trends have contributed to an alarming rate of environmental deterioration and the present lack of adequate shelter for many humans.

1.1 Sustainable Development

"Sustainability" refers to maintaining, or supporting, on a continuous basis. Based on this fundamental definition, the term "environmental sustainability" has adopted various meanings. One such interpretation refers to the "carrying capacity" of the earth, which is "its ability to provide the resources required to sustain life while retaining the capacity to regenerate and remain viable" (*Public Technology Inc., 1996*). In the context of building construction, the concept of sustainable development refers to managing building resources of the earth today so as to provide equal opportunity for future generations. This is important simply because building construction requires the consumption of resources. Consider the following statistics (*Public Technology Inc., 1996*) which state that the construction and operation of buildings account for:

- one sixth of the worlds freshwater withdrawals;
- one quarter of the wood harvest;
- two fifths of materials and energy flows;

- environmental effects on water sheds, air quality and transportation patterns.

It is a fact that people need resources to live. As the population increases so does the demand for resources. With the current methods of resource management, the world cannot sustain large increases of population. Although the developed nations contribute to much greater amounts of resource depletion per capita, the population in the developing nations accounts for 80% of the total world population (*Population Reference Bureau, 1997*). Therefore, despite a small per capita consumption, the large number of contributors in the developing nations can result in a significant proportion of resource depletion. Improper agricultural practices and resource exploitation are just two examples of the developing world's contribution to unsustainability. Limiting population growth is one method of limiting the demand for resources, and thus is an important part of achieving environmental sustainability.

Another problem is the misconception that the increased use of technology improves the standard of living for all. This, of course, is not necessarily the case and technology has sometimes been described as a "two-edged sword" (*Toporow, 1991*). For example, a new highway brings efficient transportation but also brings smog to an area. This concept can also be applied to developing nations. For example, the provision of high tech logging equipment which allows for large scale clear cutting of forests. A large logging industry for a relatively poor nation can bring a well received economic boom; but without sustaining the forest, the industry may be short lived. This is not to suggest that third world countries do not deserve the same benefits as the first world, however, if and when these benefits are put into place, the education and planning necessary to properly manage them should be a requirement. Technology can be used in a favourable manner by utilizing proper resource management techniques and by recognizing the global consequences of development ahead of time.

Poor planning is also evident in the common phenomenon of urban sprawl. In developed nations, cities have developed with large industrial cores with massive arterial and highway networks providing access via automobile to and from areas surrounding the city. This planning "around the automobile" has lead to the uncontrollable emission of pollutants into the atmosphere which have contributed to global warming, ozone depletion and respiratory problems for many people.

It must be understood that resource management is of utmost importance if environmental sustainability is to become a reality. It has been estimated that to maintain the relatively high standard of living in the United States, each citizen requires the continuous production of four to six hectares of land (*Goodland et al., 1994*). Therefore, to sustain the current global population of 5.84 billion people at this level would require approximately 24 billion hectares of land. The total land area of the Earth is only 13 billion hectares.

A somewhat dire, but interesting, conclusion was drawn by a meeting of the 'Club of Rome' in 1968 (the results of which were published in a book entitled '*The Limits to Growth*' in 1972). The club, consisting of 30 scientists, economists, industrialists and government officials from 10 countries, gathered to discuss various issues of global interest including the environment and poverty. A "World Model" was developed which simulated five parameters: population, industrial capital, food, non-renewable resources and pollution. The simulation, which contained many simplifications, attempted to trace the paths of the five parameters from the year 1900 to 2010. Numerous simulation runs were conducted (slightly varying certain parameters) producing surprisingly consistent results (***Figure 1.1***). The trends are immediately evident; growth and collapse. It was stressed by the Club of Rome that the results were not intended to be quantitatively accurate, but provide a qualitative prediction.

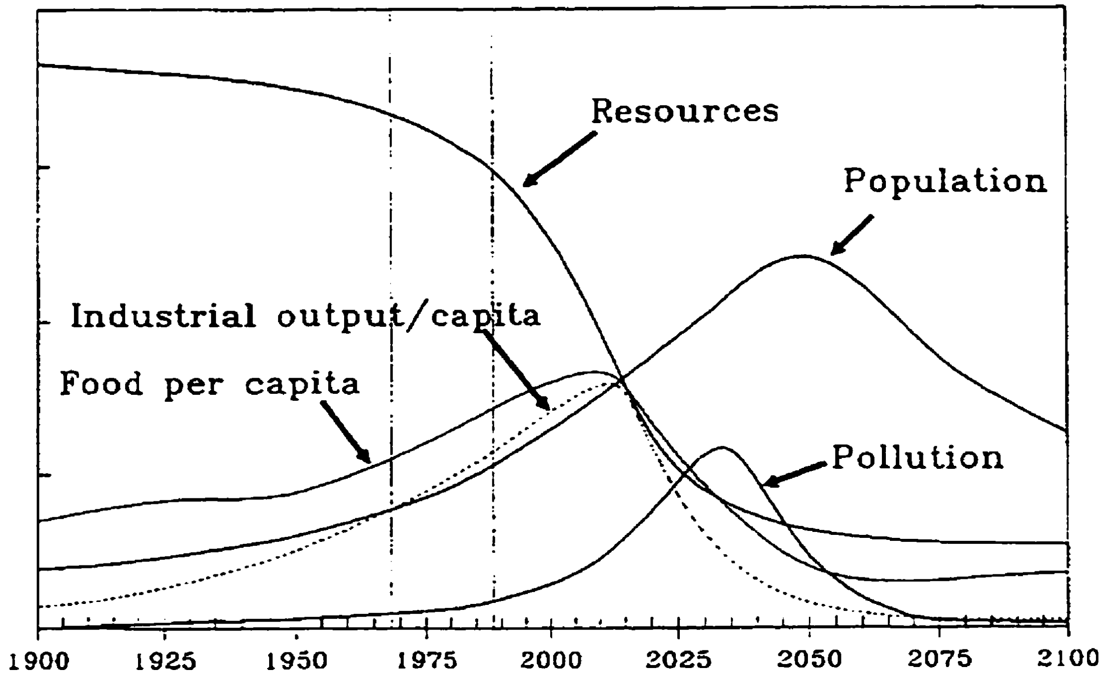


***Figure 1.1** - World Model Standard Run Output (Nalder, 1991)*

Responses to the Club of Rome's predictions are varied. In a paper prepared by Nalder in 1991, the *actual* paths of the parameters from 1968 to 1990 are compared to the *predicted* paths forcasted in 1968. Nalder concluded that the predicted trends have followed the actual trends reasonably closely over the past 20 years and therefore the serious environmental concerns concluded in the Limits to Growth are justified (*Nalder, 1991*). Others have severely criticized the *Limits to Growth* for stating that the world would runout of specific resources, yet it has not (*Sanera and Shaw, 1996*; *Bailey, 1993*). Norton comments that *Limits to Growth* has been misrepresented as a "gloom and doom book", stating that the book clearly acknowledges its own limitations; a fact that authors such as *Sanera & Shaw*, and *Bailey* fail to mention (*Norton, 1997*). There are many views, many opinions and many interpretations of the work conducted by the Club of Rome; which incidentally, still exists and continues to present environmental concerns to the world today.

It is the opinion of the author of this thesis that sustaining the environment is a real concern today since continuing present trends will undoubtedly result in more difficult times for future generations. The absolute degree of environmental decay, however, is indeterminate. Conducting the world's day to day activities in a more environmentally conscious manner by managing population growth, a better use and understanding of the role of technology, and better community planning is important in achieving environmental sustainability.

1.2 Affordable Shelter

The unavailability of affordable shelter has become a global concern and as such, the topic has received much attention. A review of the literature reveals characteristic trends which have been identified to contribute to the current shortage of affordable housing, many of which bear striking similarity to the trends threatening environmental sustainability. The trends which are briefly discussed below are population growth, increased levels of poverty versus increased housing costs, rapid urbanization and urban sprawl (squatter settlements), lack of education for self-help housing (housing self-built by the occupant), and failed government policies.

The first concern is overpopulation. The mid-1997 world population stands at 5.84 billion, and is projected to increase to 6.89 billion by 2010, and 8.04 billion in 2025 (*Population Reference Bureau, 1997*). This translates to a new housing demand of approximately 20 million units per year to satisfy the population increase alone. Of critical importance is the fact that third world developing countries will account for 98% of this growth, hence the importance of providing affordable housing designs.

Poverty and poor living conditions are an issue in developed and developing nations. An increase in average construction and land costs coupled with a smaller increase in average income levels have resulted in less people being able to afford adequate shelter. Consider the following statistics from the United States (*Zarembka, 1990*): In the period between 1974 to 1983, the median monthly rental rate increased by 188% while the median monthly salary increased by only 89%. It was also estimated that in 1985, 7.5 to 8.1 million U.S. households were living below the poverty level and $^{2}/_{3}$ to $^{3}/_{4}$ of them did not receive any government financial aid or public housing. Although housing quality has improved in the United States since World War II, this has been overshadowed by the deterioration of existing housing units, where an estimated US$9 billion is needed in repairs and US$20 billion for modernization. Developing nations are reporting similar problems. For example, in Zimbabwe, it is estimated that 54% of the population cannot afford a "standard" 4 room home (*Mafico, 1990*), indicating that the real needs of the people are not being satisfied.

High levels of poverty and unemployment, and increased housing and land costs have contributed to the formation of "squatter settlements" surrounding many urban centres in developing countries. This form of urban sprawl mainly represents people who have obtained employment in urban centres, but cannot afford accommodation within the city. As a result, they illegally occupy land on the outskirts of the city and self-build their shelter. Squatter settlements are known for their overcrowded conditions, poorly built homes and inadequate engineering systems (water supply, drainage, storm and sanitary sewers, solid waste disposal programs, transportation to and from urban centres). A large part of the problem is blamed on poor planning, in that, where the city has lower income jobs, it does not have the appropriate housing to accommodate the workers. In 1983, almost 114,000 squatter households lived in India; and in Rio de Janeiro, Brazil, approximately $^{1}/_{5}$ of the urban population lives in squatter settlements known as "favelas" (*Basu, 1988*). Urban slums are often considered to be the developed nations equivalent to squatter settlements.

The shelter solution for many low income wage earners in developed and developing nations is through "self-help" housing. This involves a homeowner building his/her own dwelling using locally available materials. There are many promising outcomes possible from this strategy, some of which will be emphasized later in this report, however there are also many problems. A lack of education and technical training for self-builders often results in structurally inadequate designs, improper maintenance and accelerated deterioration. Also, many self builders attempt to imitate urban designs without knowing the actual costs involved, consequently, homes are left unfinished.

One of the primary concerns of government is to help ensure the social well-being of the society it governs. In an attempt to accept the social responsibility of providing adequate shelter and to provide better living conditions for all its people, governments all over the world have adopted various subsidy programmes, public housing projects, rent control schemes and squatter clearance initiatives. Despite these efforts, a deficiency in affordable housing continues to exist (see *Zarembka, 1990*).

In summary, providing affordable homes to meet the forcasted demand involves attention to population growth patterns, improved community planning, a reduction and/or control in construction and land costs, and increased education for the consumer/self-builder.

1.3 The Role of the Civil Engineer

The adequate supply of affordable housing within an environmentally sustainable context is an important concern as the modern world enters the next millennium. The solution to this problem requires a global commitment to the understanding of the interaction between community development and environmental impact, and the application of this understanding in the decision making structure. This demands a multi-disciplinary effort among policy makers, planners, designers, constructors, and consumers.

Engineering is problem solving. The word "civil" can be defined as, "belonging to the people" (*Oxford American Dictionary*). Therefore, civil engineering may be described as a profession dedicated to solving problems related to the people and hence, the community. The provision of affordable housing is clearly in the domain of civil engineering since it is a community related problem where the people are directly affected.

How can engineers improve the current state of housing? Successful sustainable affordable housing utilizes available resources (e.g., raw materials, labour, equipment) in the most efficient manner possible. That is, the design of the house must be optimized. It is therefore an innovation in the approach to housing design that can provide a reasonable step to the attainment of sustainable affordable housing.

This innovation can be accomplished utilizing a *civil engineering systems approach*. In general, a *civil engineering system* can be defined as a decision making methodology which enables optimized design through the proper consideration of all relevant design parameters and their interrelationships. By applying this methodology to housing design, the civil engineer may identify parameters which influence total cost, quality and environmental impact and make design decisions which optimize these parameters to produce a truly sustainable affordable housing unit.

This report will endeavor to provide the reader with an understanding of what constitutes a sustainable affordable house and how sustainable affordable housing can be designed using a civil engineering *systems approach*. Past and present housing programs and innovative design techniques are also presented to show the progress of housing supply which attempt to utilize a sustainable and/or affordable concept.

1.4 Report Outline

Chapter 2 - Civil Engineering Systems describes the general characteristics of a civil engineering system and the systems design approach.

Chapter 3 - Planning Stage initiates the systems design approach as specifically applied to the design of sustainable affordable housing by presenting the universal goals, objectives, and constraints. The information needed during the planning stage is also discussed.

Chapter 4 - Design Synthesis provides design recommendations and information via sample case studies to aid the design engineer in synthesizing a near optimum design(s) prior to model development and evaluation.

Chapter 5 - Evaluation and Optimization presents a method of evaluating a synthesized sustainable affordable house design and the process by which the design is optimized.

Chapter 6 - Sample Design Procedure presents a hypothetical case study for the purpose of demonstrating the proposed systems design procedure and to help identify potential decision making conflicts in the specific context of sustainable affordable housing. Other examples as they apply to the general field of civil engineering are also briefly presented.

Chapter 7 - Conclusions summarizes and discusses the findings of this research and provides direction for future research initiatives.

CHAPTER TWO

CIVIL ENGINEERING SYSTEMS

The civil engineering profession is responsible for solving problems with the ultimate goal of satisfying needs of the community such as mobility, power generation and water supply. Solutions to these needs are manifested in the design and construction of large civil engineering projects such as highways, power plants, and municipal services, respectively. Many designs may meet the requirements of the project, however only one can be implemented. Choosing the best design requires careful consideration of the parameters affecting it and an understanding of how the design will react to changes in those parameters. The essence of *systems design* is to recognize the entire design procedure, from conceptualization to end of life, as a series of interrelated *design variables*. The goal of this chapter is to represent a civil engineering project as a system, and to present the steps involved in a structured decision-orientated systems design method.

2.1 The Civil Engineering Project

Typical civil engineering projects, can be divided into four distinct phases (*Templeman, 1982*); planning, design, construction and operation.

Planning involves analysis of the problem. The objective is to define the purpose of the project, and collect data to determine the constraints, goals and performance criteria. Planning can offer a measure of the feasibility of the project, for example, research may reveal a cost much greater than originally anticipated therefore not making the project worthwhile to implement. The civil engineer's role in this phase is to provide technically relevant information for decision makers (often government agencies) which outlines the costs, benefits, advantages and disadvantages of the project. This facilitates informed decision making.

Design involves determining a specific method of achieving the goals identified in the planning stage. A common end product of this phase is a set of drawings and specifications which present details of the project and constitute a design package. Civil engineers are often responsible for the technical design and assembly of the design package.

The *construction* phase turns the design into a reality by the physical assembly of the design using the specified materials and techniques suggested in the design phase. Usually a contractor is hired to perform the construction duties and the civil engineer must act as an impartial liaison between the contractor and owner. The role of the engineer is to ensure that the work is completed on time, within the anticipated budget and that the requirements of the contract are met.

The *operation* phase is not always considered in the design of a civil engineering project, but it is very important in terms of cost and quality. This phase involves monitoring the performance of the project and assessing the degree to which it is fulfilling its intended purpose. Based on the information gathered during the operation phase, the civil engineer may make recommendations for repairs and/or upgrades. This, in effect, is an appraisal of the system. General maintenance is also a part of the operation phase.

Inherent in each phase of a civil engineering project described above is the need for creativity, good judgment and decision making. Although these required skills are primarily developed through experience, good decision making techniques have been well formulated within a scientific approach and thus, can be studied and practiced. Another important characteristic of the phases is that they can overlap. For example, the design of a structure may be changed due to a difficulty in constructing a component of the original design. Therefore, although the phases are distinct in their roles, one usually cannot be totally completed without recognizing potential impacts on, or from, the other phases. All four phases are necessary for completion of a project, and collectively, they form a *civil engineering system*.

2.2 Systems Design

Systems design provides a logical, comprehensive framework for the decision making process used in the planning, design, construction and operation of a civil engineering project. This process "marks a precise path that guides creativity toward the best decisions" (*Merritt & Ambrose, 1990*). In general, systems design asks the following questions (*Templeman, 1982*);

1. What decisions must be made?
2. How are the decisions related and what external factors limit them?
3. What criteria determine whether the decisions made are good or bad?
4. How can the best decisions be made?

The formal framework for a systems design process begins with the definition of the problem. The problem definition includes the geographic and temporal scope of the project and identification of the *stakeholders*. Stakeholders represent all people and/or organizations who may be affected by the problem. Identifying the problem, scope and stakeholders can require extensive background research and is an important first step in the process.

Once the problem has been properly identified, specific *objective(s)* of the project are determined. The objectives indicate the fundamental *goal(s)* of the project and should capture all the effects on, and interests of, the various stakeholders. Objectives are usually stated in a form of "minimize" or "maximize"; for example, the design of a beam may require to "minimize cost and minimize mid-span deflection". The relative merit of a design can be evaluated based on how well it meets the desired objectives.

Constraints must also be defined for the problem. Constraints are strict conditions that cannot be violated. For example, there may be an allowable maximum deflection to satisfy serviceability conditions for a local building code. The final design must exhibit characteristics which obey the constraints of the problem. Designs which violate a constraint are considered unfeasible and cannot be implemented. It is important to note that "constraints" should not be confused with "difficulties". For example, the total budget for a project may be \$100,000, however, if the final cost of a design is \$100,100, it would be unrealistic to exclude it as unfeasible. An increase in the budget may be difficult, but it usually is not impossible and thus, would not be considered a constraint.

With a proper problem definition and identification of the goals, objectives and constraints, *alternative* designs can be formulated. This is the process of *design synthesis*. This stages requires the decision maker to create one or more potentially feasible designs based on experience and research. For example, based on beams used on other projects (where information regarding the cost and performance of the beams is available), the designer can recommend alternative designs which differ materially and dimensionally.

For each alternative formulated, the creation of a *model* is required. A model is a representation of the actual system where the design is defined as a system of design parameters or *variables*. A representative model can be physical (e.g., scaled down prototype structure), mathematical (e.g., set of equations to be simultaneously solved) or conceptual (e.g., set of questions to be systematically answered). The purpose of the model is to predict the performance of the system based on a given set of *criteria*, and to observe how the system responds to changes. The criteria provide a method of measuring how well the synthesized design alternative meets the goals and objectives of the project, and thus, provides an *evaluation* of the design.

The formation of variables to define an alternative is a key concept in systems design. *Independent variables* represent imposed conditions on the system and can be further divided into variables which the designer has control over (*controllable* independent variables) and no control over (*uncontrollable* independent variables). In the design of the beam, for example, the depth of the beam is a controllable independent variable while the load the beam will be subjected to is an uncontrollable independent variable. *Dependent variables* are those which represent the response or performance of a system and are a function of the independent variables. For the beam example, the mid-span deflection is a dependent variable which is, in part, a function of the depth of the beam and the imposed load.

Therefore, design synthesis involves determining the independent variables, and the model predicts the performance based on the established functional relationships of the dependent variables.

The ultimate purpose of the systems design approach is *optimization*. The optimum design is the alternative which makes the most efficient use of available resources to effectively satisfy the objectives of the project within the specified constraints. When only one objective exists (e.g., minimize cost), determining the optimum solution is simple (i.e., the one with the lowest cost). However, when multiple objectives exists, determining the optimum design can be difficult. For example, dual objectives in the beam design example were to minimize cost <u>and</u> minimize mid-span deflection. Suppose the following two alternatives were generated;

Alternative 1:	cost \$1,000	deflection 3mm
Alternative 2:	cost \$1,500	deflection 2mm

Which alternative represents the optimum solution?

The process of optimization, therefore, requires that alternatives are narrowed down until only one, representing the best solution, remains. The process of elimination begins with identifying unfeasible alternatives. Unfeasible alternatives are ones which violate constraints or are totally dominated by another alternative. For example, a beam costing $2,000 with a deflection of 4mm is clearly inferior to the two alternatives described above, consequently, it can be neglected in further analysis. When two or more potentially feasible alternatives do exist, a *sensitivity analysis* is warranted. A sensitivity analysis involves careful consideration of the relative *tradeoffs* among alternatives. For the two beam alternatives, the following question would be considered: "Is the benefit from a reduction in the mid-span deflection of 1mm worth the monetary equivalent of $500?". If the answer is "Yes", then Alternative 2 would be optimum.

In a complex civil engineering system, clearly identifying all design variables and describing exactly how they are interrelated can be very difficult. When the notion of *intangible* variables is introduced (i.e., variables difficult to define quantitatively), the system's complexity increases. In the relatively simple beam design example, determination of the optimum design requires an assessment on the "value" of 1mm of deflection. It is postulated that when a systems approach is thoroughly followed, the necessary information to intelligently answer this question will be available for the decision maker.

Generating multiple alternatives for a complex systems may not always be an efficient practice for optimization. Thorough planning and research can provide the decision maker with a wealth of information so that a very viable "first guess" is achieved. Optimization would then proceed through a sensitivity analysis approach whereby the system model is analyzed and areas of potential improvements are identified. Small changes in the design variables are made, and the new response, or performance, of the system is observed. If the response is better than the previous, the optimization process may be continued with the new design, otherwise, subsequent changes of the previous may be attempted. In this case, the decision maker must decide when optimization has been reached. Definition of this point is dependent on the objectives of the specific problem being investigated.

A structured decision-making systems design approach (***Figure 2.1***) provides the information necessary determine an optimum design among several alternatives. This is accomplished by guiding the decision maker through a process of thorough analysis. Thorough analysis aids the decision maker by identifying important design information and organizing that information into a structured form, consequently the creativity and judgment skills of the decision maker are brought out. This is the essence of systems design, and will help result in intelligent decisions and optimized designs.

2.3 The Housing System

In order to develop a design methodology for sustainable affordable housing, the theory of civil engineering systems must be directly applied and presented in a format conducive to a structured decision making approach. ***Figure 2.2*** illustrates the specific steps involved in the systems design of sustainable affordable housing. Each of these steps are described in detail in subsequent chapters of this report.

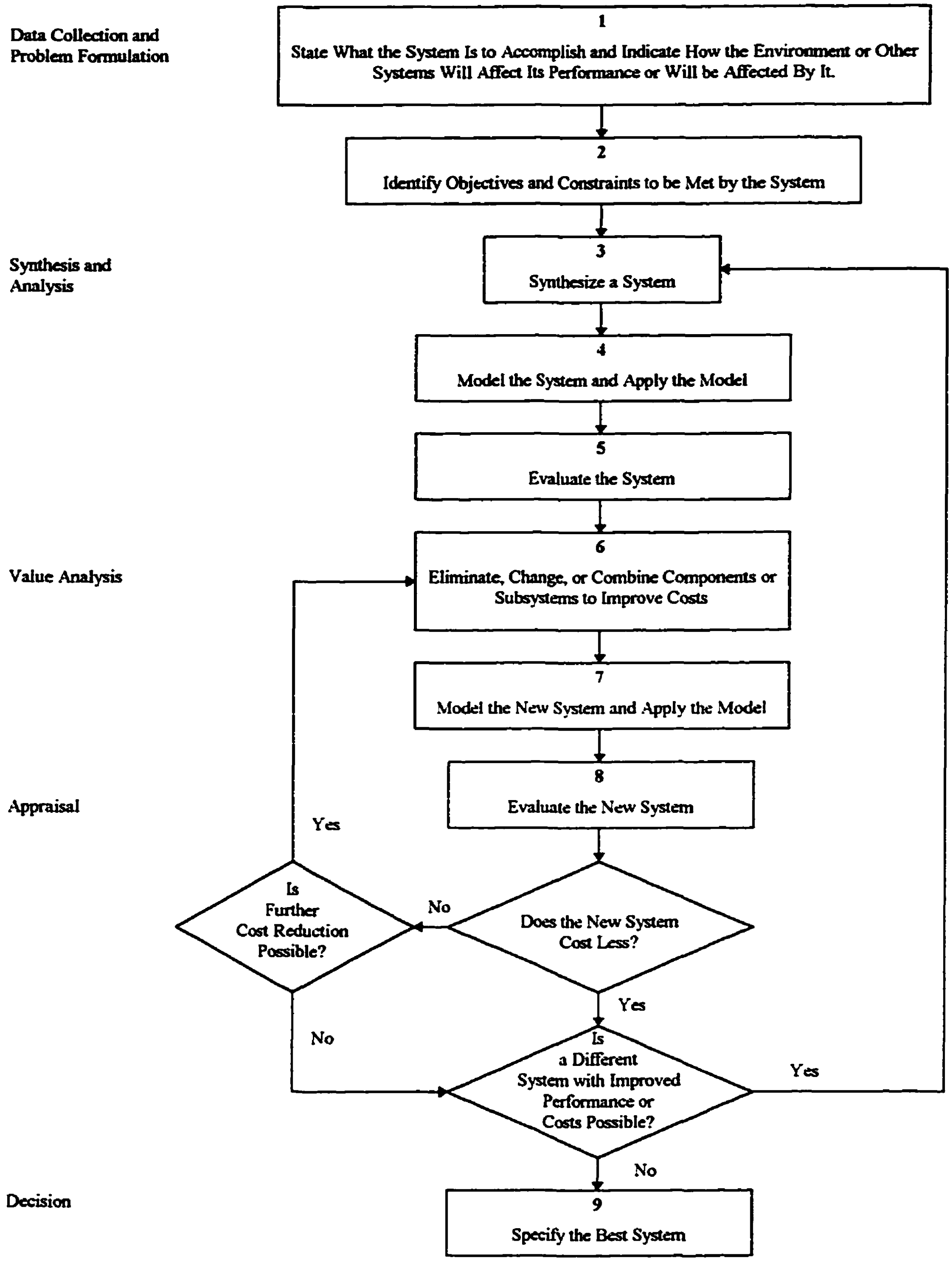


***Figure 2.1** - Flow Chart of Systems Design Approach (Merritt & Ambrose, 1990)*

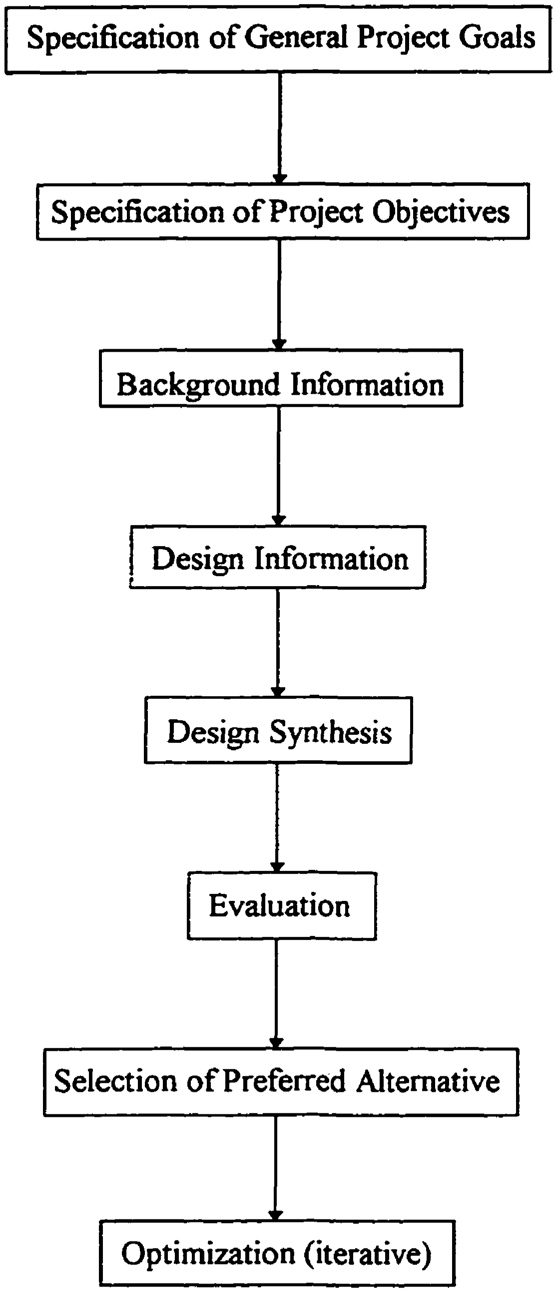


***Figure 2.2** - Sustainable Affordable Housing Design Methodology*

CHAPTER THREE

THE PLANNING STAGE

Housing provides people with many basic requirements which include protection from the natural environment, economic stability via home ownership, a sense of identity within a community and an element of privacy. The design of a sustainable affordable home should satisfy these basic requirements by selecting design components which when combined, create an optimum total package in terms of cost and environmental impact. Systems design is not a recipe, but an approach which emphasizes a whole as being greater than the sum of its parts. By considering all phases of the civil engineering project during the systems design process, the engineer can establish a complete picture of what the design should accomplish. This effectively shortens the optimization procedure by increasing the probability that the first design synthesized will be close to optimum. *Systems design facilitates informed decision making.*

This chapter will initiate the systems design approach by presenting a fundamental goals and objectives for a sustainable affordable housing project and comment on the information requirements necessary for design synthesis. Together, these steps form the *planning stage* for systems design.

3.1 Goals and Objectives

Chapter 1 presented some of the issues related to environmental degradation and the lack of affordable shelter. The need for sustainable affordable housing is based on the premise that continuing the present environmental and housing trends are undesirable, that is, housing must meet the demand for shelter for people of all income levels while managing environmental resources so not to compromise the opportunity for future generations. This can be applied to all areas of the world; developed and developing nations. Therefore, the general *goal* of any sustainable affordable housing project is to *provide environmentally sustainable homes that meet the required demand for shelter in terms of cost, quality and market acceptance*.

The next step involves identifying the *objectives* of the project. As mentioned in *Chapter 2*, the objectives of the project should capture all the effects on, and interests of, the various stakeholders. If improperly defined, an otherwise perfectly executed systems design procedure will not result in an optimum design.

A general set of objectives may be formulated based on the fundamental *performance* requirements for any sustainable affordable home. It is important that the objectives only describe what the design should accomplish without suggesting how it should be accomplished (i.e., *performance* versus *design* objective). For example, *minimize cost* is a performance objective, but *maximize use of inexpensive materials* would be an inappropriate objective because it directly provides a recommendation to the engineer. There may be additional ways of minimizing the cost that may be overlooked if the latter objective is used. Specifying design objectives at this stage of the systems design process may severely limit the creativity of the engineer.

The following are the proposed performance objectives for a sustainable affordable house:

1. *Minimize Cost*

   Too often the initial construction costs of a home are overemphasized without acknowledging the total systems costs involved in a housing project. Total system cost includes the costs associated with the planning and design, construction, operating and maintenance, and disposal of the house.

2. *Minimize Environmental Impact*

   Negative environmental impact threatens sustainability. Minimizing the stress a home places on the environment can contribute significantly to achieving a globally sustainable society; thereby ensuring future generations equivalent housing opportunities. Environmental considerations exists in the materials selected, construction procedure and operation of the housing system.

3. *Maximize Social Acceptability*

   Poor housing conditions directly signify poor social conditions. Therefore, a properly designed sustainable affordable housing project can provide home owners with the positive social conditions necessary to promote strong community development. A socially acceptable house will directly address the cultural needs of the people in terms of size, affordability and function; as well as address the intangible benefits of housing such as security and safety, aesthetics, and sense of accomplishment and community.

These three objectives represent the universal, performance based requirements of any sustainable affordable housing project, however, an element of geographical bias is inherent within their interpretations. Every individual location researched will have a unique set of environmental and socio-economic characteristics which can significantly alter the perception of affordable cost, required level of climatic protection and notions of social acceptability. *Therefore, although the objectives can be applied universally, the method by which they are satisfied through design synthesis is a function of the specific characteristics of the region.*

3.2 Background Information

Determining the environmental and socio-economic characteristics of a particular region involves a well organized and thorough research effort, the goal being to develop a comprehensive profile of the people, environment, climate, resources, economics and politics for the purpose of identifying the true housing need, demand and constraints. Although more research generally equates to a better understanding of the situation, it also means more resources. Since cost is an issue in the design (as stated in the objectives), then there must be an optimum balance between the amount of information obtained and the time spent gathering that information. A true systems design must address this conflict. Often a research program is limited due to an absolute time and/or financial constraint imposed by the contract. If a physical constraint does not exist, the engineer may be left to make a judgment call as to when enough information has been compiled to initiate design synthesis.

The following list represents the minimum information requirement for the planning of a sustainable affordable housing project:

1. What is the climate of the region?
   - average monthly high/low temperatures, humidity, wind speed
   - is there a potential risk of earthquakes, floods, severe storms, volcanic eruptions

2. What is the projected housing demand?
   - estimate number of homeless
   - estimate population growth rate
   - how many homes need to be immediately built
   - are there abandoned villages nearby
   - is there an opportunity to rebuild or renovate
   - what are the future development plans in the area

3. How much should the homes cost?
   - estimate monthly family income
   - what is the average cost of a current home
   - what are people willing to pay for a home

4. What type of homes should be built?
   - what are people accustomed to
   - what amenities are expected in a new home
   - how do the cultural conditions affect housing design

5. What is the current housing situation in the area?
   - who builds the current homes
   - how are the current homes paid for
   - are current housing conditions satisfactory
   - is the housing demand being met
   - what type of materials are used

3.3 Design Information

The background information assembled is intended to provide the engineer with a profile of the geographic location. The next step is to use this information to derive additional parameters needed for the physical housing design. These additional parameters fall into three broad categories: economic, physical attributes and building science, which are described below.

a) *Economic*

It has been established earlier in this report that housing cost represents an objective and no formal constraint practically exists. However, design synthesis should not be initiated without an understanding of, "What is affordable?". It is therefore necessary that the engineer establish a *target cost* which may serve as a useful guideline. For example, if the prospective homeowners can comfortably afford $200,000 homes, and this is the price they expect to pay, there is no reason for the engineer to design a house that is worth in the $1,000,000 range. A procedure for determining an initial target cost estimate is presented below. Since the estimate of a target cost is just that, an estimate, the procedure and the information required for its completion are not intended to be strict or precise. However with common economical sense and good engineering judgment, evaluation of a target cost is a significant contribution to the system design of sustainable affordable homes.

The first step is to calculate an estimate for monthly living costs (LIVING); not including monthly housing costs (HOUSING). Where:

LIVING = food + clothing + transportation + education + child care + taxes/insurance + entertainment + regular savings + other costs

HOUSING = mortgage payments + maintenance + heating/cooling + taxes + other costs.

Therefore:

TOTAL COSTS = LIVING + HOUSING.

The second step is to determine an appropriate average monthly income (INCOME) for the prospective homeowners of the area. It is preferable that an income range is determined (INCOME_{low} and INCOME_{high}). This can be done by examining income and employment statistics. Assume that a family's total monthly expenditure (TOTAL COSTS) must be less than or equal to their total income (INCOME); that is, they must be able to pay all their monthly expenses with the income they earn.

From the above discussion, the following range of total monthly housing costs can be deduced:

$$\text{HOUSING}_{low} = \text{INCOME}_{low} - \text{LIVING}$$
$$\text{HOUSING}_{high} = \text{INCOME}_{high} - \text{LIVING}$$

Since the total monthly housing cost (HOUSING) includes the mortgage cost and operating/maintenance costs of the home, it is desirable to isolate the mortgage cost from this total. This can not be accurately done before design synthesis is complete since operating/maintenance costs of the home are unknown, however, for the purpose of determining a target cost, an assumption may be made based on average values for existing homes in the area being studied. That is, an approximate percentage of the ratio: MORTGAGE / HOUSING needs to be assumed.

Finally, once the allowable monthly mortgage is calculated, a target cost may be calculated based on existing information of currently accepted financing practices (bank loans, interest rates, government subsidies, etc). For example, if it is determined that $700/month can be safely afforded for a monthly mortgage (principal and interest), with a downpayment of 25%, an interest rate of 7% and a repayment period of 25 years, the target cost would be:

> $700/month @7% for 25 years: principal = $99,000
> add 25% down payment of $25,000
> therefore, target cost = $124,000

b) *Physical Attributes*

The physical attributes of a house are of obvious importance in design. Prior to design synthesis, the engineer should have a mental picture of what physical elements an ideal housing design, for the specific geographic area, should embody. Information regarding the expectations and lifestyle of the people of the area is therefore needed, hence the background information exercise.

At this stage of the systems design procedure, the following information is required:

- recommended number, size and type of the following rooms:
    - bedroom
    - washroom
    - kitchen
    - family
    - living

  * dining
  * laundry
  * study/den
  * storage
  * garage
  * other

- recommended amenities:
  * electricity
  * hot/cold water
  * livable basement area
  * air conditioner
  * central vacuum
  * alarm system
  * other

- recommended services:
  * sewers/septic
  * natural gas
  * telephone
  * television
  * other

- general design issues:
  * lot size
  * detached, semi-detached, townhouse, condominium
  * single/multi-storey
  * other

c) *Building Science*

A fundamental requirement of a house is to protect the occupants from external environmental conditions imposed on the house (e.g., extreme temperatures, wind, precipitation, moisture, noise, wildlife, earthquakes, floods, etc.). A house which does not meet this basic requirement is wholly inadequate. To address these building science concerns, building codes are enforced in defined geographic areas to promote consistency, help reduce structurally and functionally inadequate designs, and to offer significant time savings in the housing design and construction process. However, they can also negatively affect the affordable housing market by forcing an overdesign and thus, higher costs than actually necessary. If a home is designed based solely on satisfying the performance objectives, and the engineer is free to synthesize an adequate design without building code restrictions, a greater potential for lower cost homes can be realized.

An interesting perspective related to building codes comes from the reference *Handa, 1989* (original reference: *Kaufman, M.T. 1989*). A "homeless" person built his shelter (measuring 10' by 10' by 4') using plywood, carpet and plastic sheets. The total cost was approximately $0.80/ft^2 (1989, US dollars). Two couples lived in this house which they perceived as being "comfortable". Lavatory facilities were available from a nearby taxi garage where the homeowners were acquaintances of the manager. An added advantage expressed by the homeowners is that they could disassemble the home and move to a new location if they so desired. In the perception of the homeowners, this home adequately satisfied their objectives in terms of cost, quality and acceptability. Therefore, it may be assumed that a government subsidized home, in a fixed location, built to building code standards and costing significantly more would not be a feasible option for them. If there needs are being met, why would they pay more to change? Do governments, designers or engineers have the power, or ability, to force a definition of an acceptable housing standard upon the people via a building code? Surely the people should not be left entirely on their own since durable house construction requires a significant degree of technical know-how, in addition, organized community planning is necessary for large scale community based sustainable affordable housing efforts.

Building codes should therefore be used as a source of information in the design synthesis process as opposed to a formal design constraint. Based on the climatic conditions unique to the area, it is recommended that the engineer determine a set of ***minimum acceptable standards*** which may serve as constraints to govern the design. This of course may not be possible in the political climate of the location in question (e.g., government may enforce stringent code practices without compromise), in which case, building code will represent true constraints.

When researching an area, evidence of code infractions in the current housing construction indicates that the cost or methods necessary to comply with the code are beyond the financial and/or technical means of the homeowners, therefore a case should be presented to justify a design based on minimum engineered standards.

CHAPTER FOUR

DESIGN SYNTHESIS

The design synthesis stage is where the design engineer must combine information about the housing location with experience, creativity and ingenuity to design alternative systems (or system) which directly meet the goals, objectives and constraints for a sustainable affordable housing project. The systems design approach dictates that once a design is synthesized, a model is created for the purpose of evaluation and optimization.

To increase efficiency in the systems design process, the engineer can increase the probability that the first design(s) synthesized is close to optimum by recognizing that the unique environmental and socio-economic conditions of a location will directly influence the physical characteristics of a house design. This chapter provides recommendations to help the engineer synthesize a near optimum initial design alternative.

4.1 Assessing True Need

Misunderstanding the true needs of the people can result in a severely inadequate design, especially in affordable housing. It is this fact that leads to many unsuccessful affordable housing projects.

A housing design for a new location is sometimes recommended based solely on its performance in other locations. The justification of using a previously proven system is that it will significantly reduce design time, save construction costs, and have an increased probability of success. Often, this may be the case, however, if the unique environmental and socio-economic conditions of the new location is ignored, the chosen design may result in cost and acceptability objectives not being met. Consider, the Asuoyebua housing scheme in Kumasi, Ghana, Africa (reference article: *Africa, 1985*) where the government was intent on providing affordable housing for the many "workers" of the country. The technology of choice was a high rise, reinforced concrete structure which had a reputation of providing savings in land, infrastructure, materials and the benefits of economies of scale. As such, the "multi-storey flats" were advertised as "low-cost" accommodation. The high standards imposed on the infrastructure, construction and finishing however contributed to relatively high final costs. The average cost per unit in Phase I of the project was C74,000; capital repayment over 35 years with a 15% interest rate would require monthly payments of C1,430 to satisfy the interest alone. Assuming households can dedicate 20% of their total income to rent, the average family would require a gross monthly income of C7,000. Less than 2% of the households earned more than C7,000 per month. As a result, although the first two blocks of the Phase I complex were nearly completed by June 1982, close to none of the units were occupied. What went wrong? The high technology, modern, cement based construction technique was simply not characteristic of the traditional Ghana lifestyle. As the author of the article states (pg 36), "the reality of Ghana is tragically so different from the ideas embodied in this scheme that it appears to have been conceived in complete indifference to the exigencies of life in Kumasi". This is a clear case of relying on a "proven" design technology without assessing whether the true needs of the intended homeowners match the actual benefits offered by the technology. If the needs were properly assessed in the planning and design phase, a more successful project would have resulted.

Another example involves the 1971 Slum Clearance Scheme in Madras City, India (*Ramamurthy, 1989*). Existing slums were "bulldozed" and replaced with multi-storey apartment complexes. Complaints that the new dwellings did not meet the technical, functional and social needs of the community were obvious; for example, some tenants maintained cattle on the third and fourth floors!

Building has traditionally been a personalized process where people have built their own houses and barns often with the help of nearby community residents. This suggests that homeowners have an instinctive "need" to be directly involved in the construction of their dwelling. With the technical advances in the construction industry during the 1900's, one may argue that the construction of houses has become much more efficient; but at what cost to the people? How many people today can successfully build a suitable dwelling for themselves that would last 100 years or more? With the advent of "technological breakthroughs" has come a loss of building skills and knowledge for the average citizen. Today, most people rely on technology to build for them, feed them, and transport them. "What is needed is new goals and ethics where technology is a tool, not an end" (*Jain, 1992*).

The instinct of being involved in one's own personal dwelling is in conflict with a technologically driven construction industry. The misrepresentation of the true needs of a community presented is testament to that. In third world squatter settlements, the physical involvement of the self-build efforts show the ability for people to band together and create a community environment, however, lack of building knowledge and attempts to imitate urban designs have resulted in poorly built homes and substandard living conditions. In developed nations, the situation is somewhat different. The reliance on technology combined with economic wealth has provided an environment more conducive to less personal involvement in the construction of private residences. This is not to say that no involvement is acceptable. Each person has their own personal tastes, therefore home builders usually allow prospective homeowners to satisfy their individuality by providing exterior and interior modifications to the pre-designed homes (e.g., colour choices, floorplan changes, etc.). Therefore, although the degree of involvement may differ according to geographic location, the instinct exists and should be addressed. Involving people will help minimize rejection and lead to more successful designs.

In third world locations, where labour is generally inexpensive and readily available, a housing system should be chosen which utilizes this idle resource. *Self-help* housing is one method of directly involving the people in housing construction. *Self-help* involves training the people to build adequate shelter for themselves. Such a system satisfies the need to directly involve the people, creates jobs where unemployment and underemployment is a continuing problem, promotes safe and adequate construction practices within reasonable economic and practical limits, and contributes to more durable and longer lasting designs since homeowners have the knowledge to properly maintain their dwellings.

4.2 Appropriate Building Materials and Technology

The materials selected for construction will directly influence the performance objectives for sustainable affordable homes. Selecting near optimum materials requires consideration of the material life cycle (MLC). The MLC, often referred to as a "cradle to grave" approach for material selection, involves identifying the stages a material experiences through its entire design life. The stages include the extraction and processing of raw materials, manufacturing process, installation, operation, maintenance and recycling/waste management (***Figure 4.1***).

As the MLC suggests, materials which are recyclable, renewable and with low values of embodied energy (i.e., "the energy required to produce and transport the material" - *Wilson, 1995*) are recommended for sustainable affordable applications. Quantitative assessment of embodied energy is discussed in *Chapter 5*.

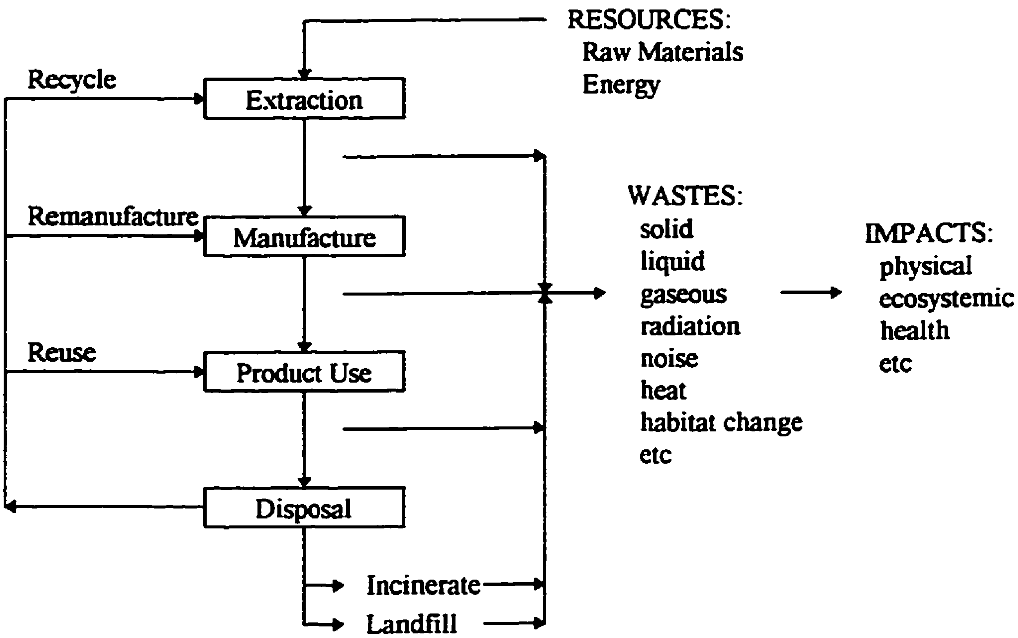


***Figure 4.1** - Material Life Cycle (Young, 1991)*

MLC considerations for building materials have also contributed to the use of *indigenous* materials. *Indigenous* is often used to describe a building material which is native to the location, naturally occurring and abundantly available. Using materials with these characteristics may result in:

a) significant cost savings from a reductions in transportation, storage and taxes associated with importing foreign materials;
b) increased sustainability from energy savings in fuel and electricity involved in the transportation and manufacturing of building materials;
c) greater probability of acceptance since local people are familiar with materials common to their immediate surroundings.

Another important environmental concern of building material selection involves toxic emissions. Many modern materials used in homes today (e.g., paints, adhesives, plastics) can emit toxic chemicals which may lead to a variety of adverse health effects. For example, improperly installed urea formaldehyde foam insulation (UFFI) used in the 1970's was found to emit high levels of formaldehyde (*Wilson, 1995*). Scientific studies are continually being conducted to assess the potential health affects of certain building materials, therefore before a material is chosen, proper research of any health risks is recommended. The following chart provides some of the sources of common indoor air contaminants (*Meckler, 1996*):

Contaminant	Harmful Effects	Source
formaldehyde	carcinogen	UFFI particleboards some paper products fertilizers chemicals glass packaging materials
radon gas	serious if exposed to high concentrations	natural radiation in soil entering through open sumps, crawl spaces, hollow concrete blocks, and cracked concrete slabs
asbestos	respiratory problems carcinogen	insulating materials surface and finishing materials
microorganisms (viruses, bacteria, fungal spores, pollen)	sneezing wheezing weakened immunity can cause serious diseases	common in many building products, furnishings and food products
combustion byproducts (CO, SO_2, NO_2, CO_2)	headaches nausea vomiting respiratory problems death	wood stoves fireplaces inverted space heaters gas stoves tobacco smoke

It is up to the design engineer to thoroughly investigate the multitude of materials available to determine their environmental, economic and practical suitability for sustainable affordable homes and to establish what potentially suitable materials exist in a given geographic locale. Some commonly available materials which have the greatest potential for future sustainable affordable initiatives include:

1. Earth

Earth (soil) has been used as a building material for many years and it is estimated that 30% of the worlds population live in unbaked earth homes (*Houben & Guillaud, 1994*). ***Figure 4.2*** shows the earthen buildings of Habban, Yemen in the Middle East, and ***Figure 4.3*** is a world map showing the predominant locations of earth residences today. The various building technologies associated with earth construction (***Figure 4.4***) can be broadly categorized into brickwork, monolithic and structure (***Figure 4.5***).

Traditionally, earth has been used in dry climates of poorer countries due to the labour intensive properties associated with building technology and earth walls susceptibility to erosion by rainwater. Earth walls kept dry however have stood the test of time in many ancient cities to prove itself worthy as a durable building material. To address erosion concerns, stabilizers (e.g., cement or lime) may be added to soil/water mixtures to create a concrete like consistency. These stabilizers, of course, add to the total cost. The benefits of earth construction are the material cost (inexpensive, readily available and durable), and environmental sustainability (natural and non-toxic).

The challenge for engineers is to devise methods of utilizing the material cost and environmental benefits of earth within a technically feasible building technology conducive to the conditions of the geographic area in question. *Cast Earth* is one such application which combines soil, water and calcined gypsum (stabilizer, 10-15% by mass) with a machine intensive continuous pour technology (monolithic construction). This relatively high-tech method yields initial construction costs comparable to conventional wood framed homes typical of the Western world, however, life cycle benefits attributable to the great thermal mass and environmental sustainability of earth walls may be realized (*Cast Earth, 1997*). The suitability of the Cast Earth technology is currently limited to more developed countries where the prospective homeowners can afford the relatively high initial costs.

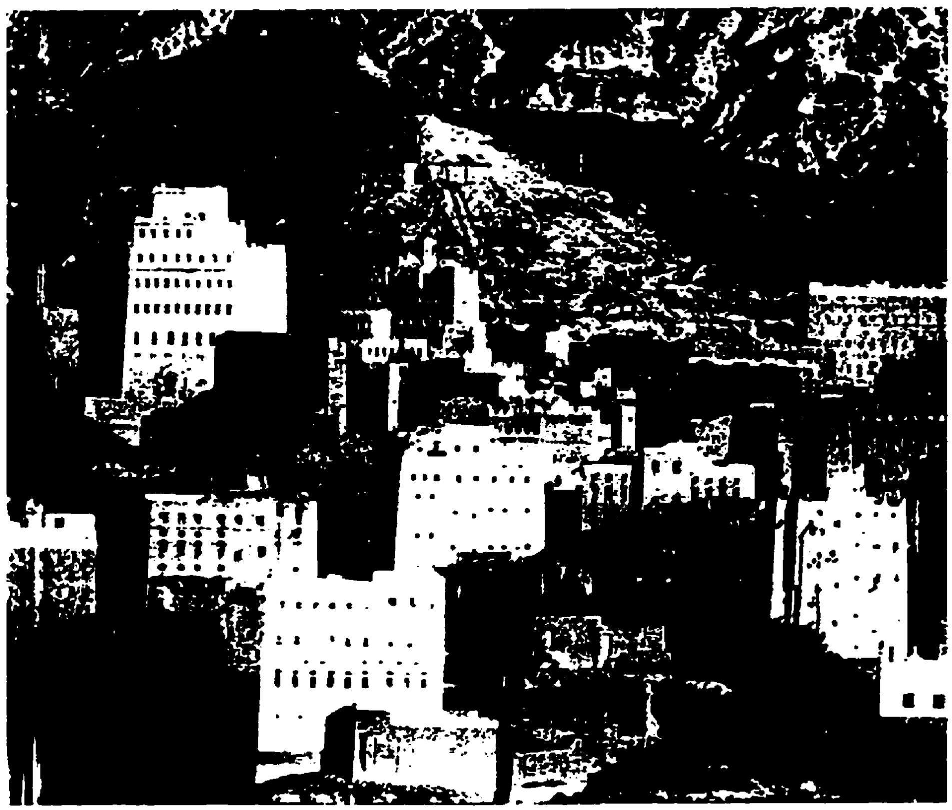


Figure 4.2 - Earth City of Habban, Yemen (Houben & Guillaud, 1994)

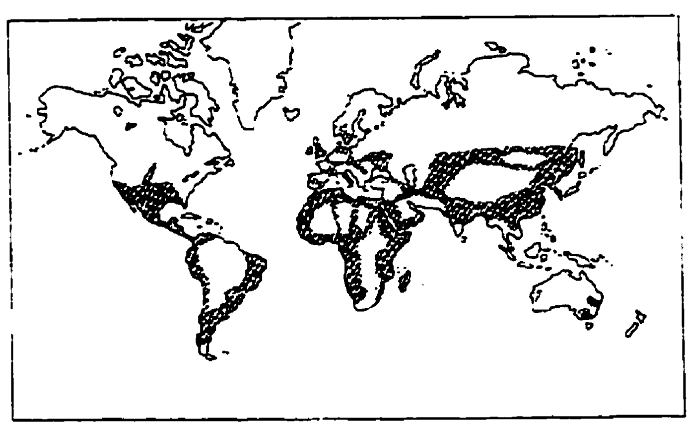
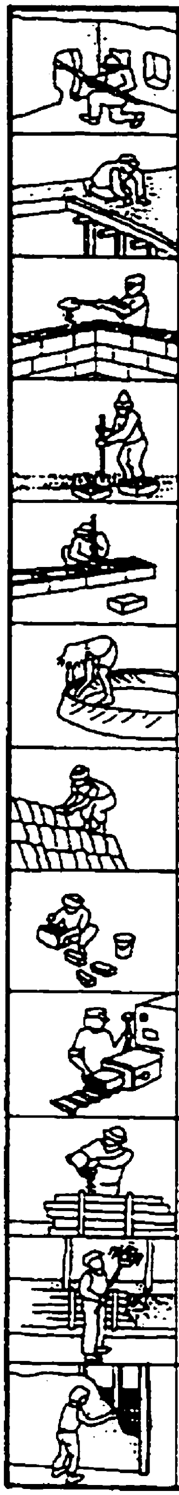


Figure 4.3 - World Earth Housing Locations (Houben & Guillaud, 1994)



1 - DUGOUT	Dwelling dug directly out of a layer of the earth's crust.
2 - EARTH-SHELTERED SPACE	A structure built in one or other material, but not earth, is encased and covered with soil.
3 - FILL-IN	Ungraded soil is used to fill hollow materials used as a framework.
4 - CUT BLOCKS	Blocks of earth are cut directly from the ground.
5 - COMPRESSED EARTH	Blocks or massive walls are formed by compressing soil in molds or formwork.
6 - DIRECT SHAPING	Thin walls are built by direct manual shaping of plastic soil.
7 - STACKED EARTH	Thick walls are built up by piling up balls of earth on top of one another.
8 - MOULDED EARTH	Earth is moulded either by hand or in moulds of various shapes.
9 - EXTRUDED EARTH	A soil paste is extruded by a powerful machine and building elements are then made from the extruded material.
10 - POURED EARTH	Liquid soil poured into formwork or moulds serves as a kind of concrete.
11 - STRAW CLAY	Also know as claw-straw, this is a slurry consisting of clayey soil binds shreds of straw fibre to produce a fibrous material.
12 - DAUBED EARTH	Clayey soil mixed with fibres is applied in a thin layer to fill in a support.

Figure 4.4 *- Earth Construction Methods Summary*
(Houben & Guillaud, 1994)

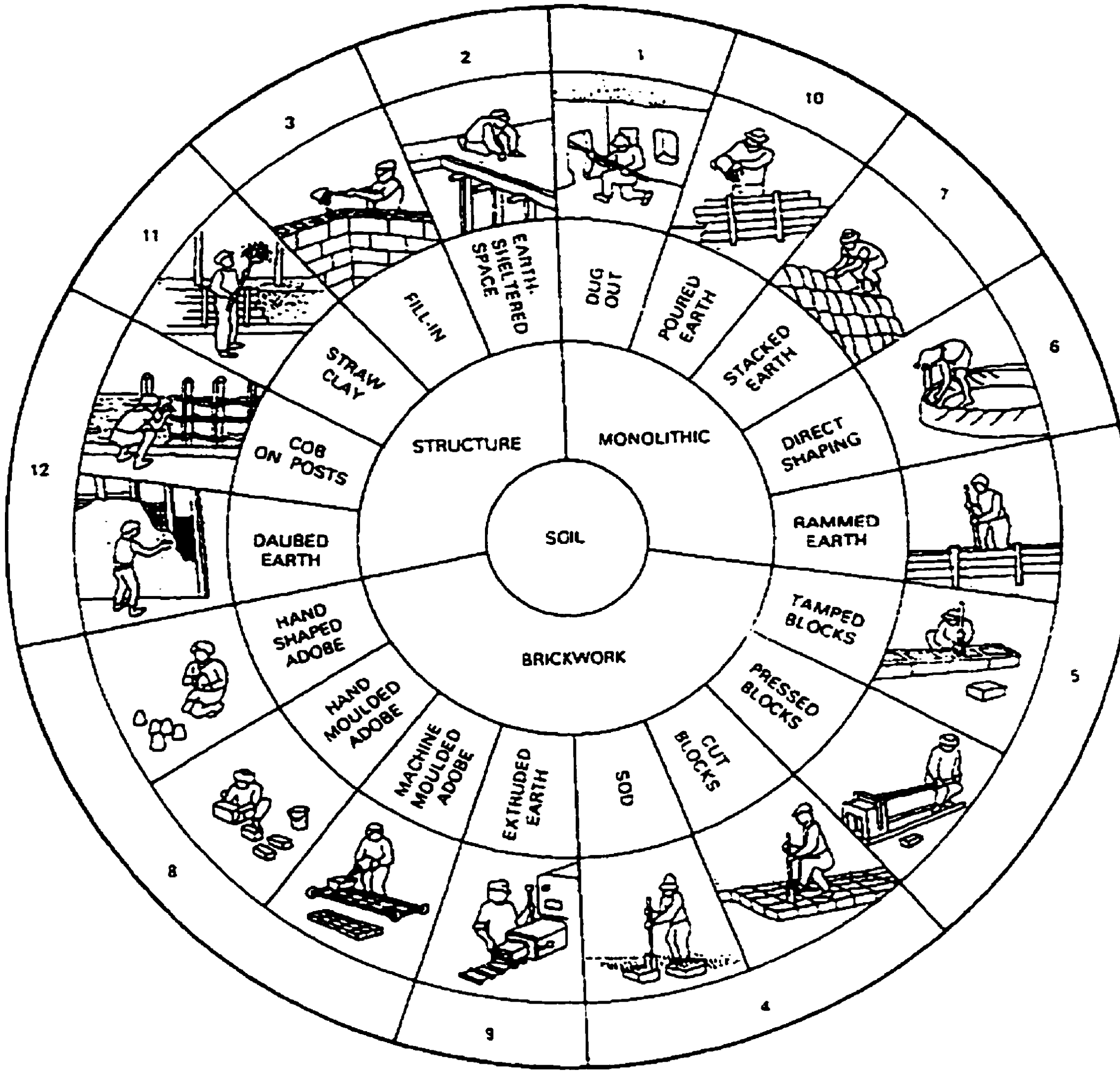


***Figure 4.5** - Earth Construction Methods Diagram (Houben & Guillaud, 1994)*

2. *Straw/Clay*

Straw is also discovering a re-birth as a building material as the world recognizes the importance of sustainability and the need for lower cost homes. Straw is a truly sustainable material since it can be regrown on an annual basis to facilitate the construction of new homes.

Two main uses of straw in house construction are *straw/clay* mixtures and *strawbale* homes. *Straw/clay* is a hybrid of earth construction where the insulating characteristics of straw are combined with the durability of earth. One such method involves spreading straw out on the ground, dampening it with water, lightly coating the straw with a clay/water mixture, then allowing the 'sheets' to dry into a strong compound (5-10% clay, 90-95% straw). Another similar method involves building wall formwork and 'stuffing' the clay coated straw into the formwork. A 12 inch thick wall constructed in this manner can provide an R-40 insulating factor.

Strawbale homes involve stacking (like bricks) full bails of straw, pinned with rebar or wooden dowels, to form walls (***Figure 4.6***). The walls are then coated with a stucco or plaster to form a continuous earthen look (***Figure 4.7***).

Figure 4.6 *- Strawbale Structure (Yellow Mountain, 1996)*

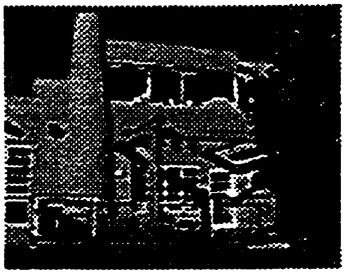


Figure 4.7 *- Finished Strawbale Home (Yellow Mountain, 1996)*

3. *Waste Products*

Another innovative attempt at resolving the sustainability issue involves homes being built with waste products such as tires and pop cans. Enter the world of the *Tire House*, where used tires are stacked and each layer is filled with earth as the wall is built up. As in the strawbale homes, the walls are finished with a stucco or plaster (***Figures 4.8*** to ***4.11***).

Figure 4.8 *- Tire House Wall Construction (Yellow Mountain, 1996)*

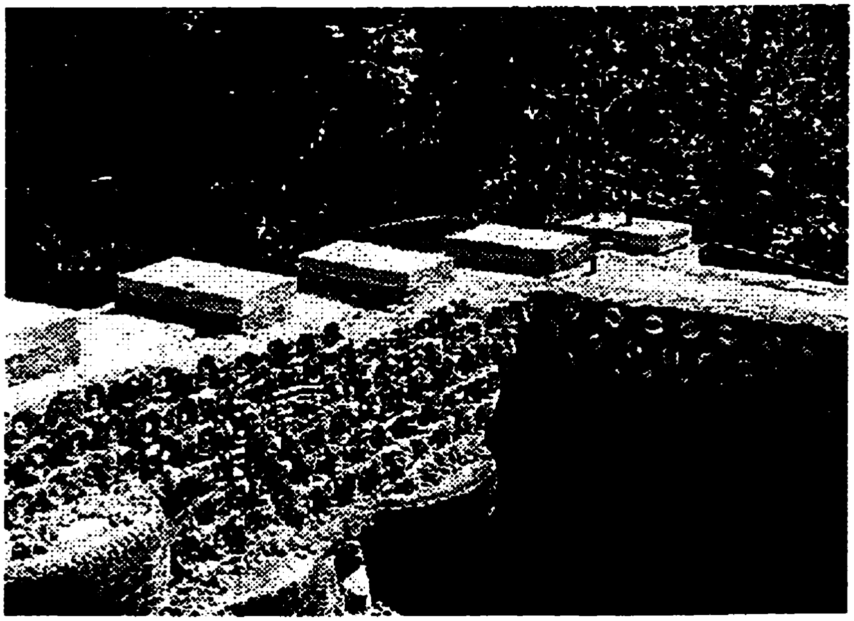


Figure 4.9 *- Tire House Top Course With Cans (Yellow Mountain, 1996)*

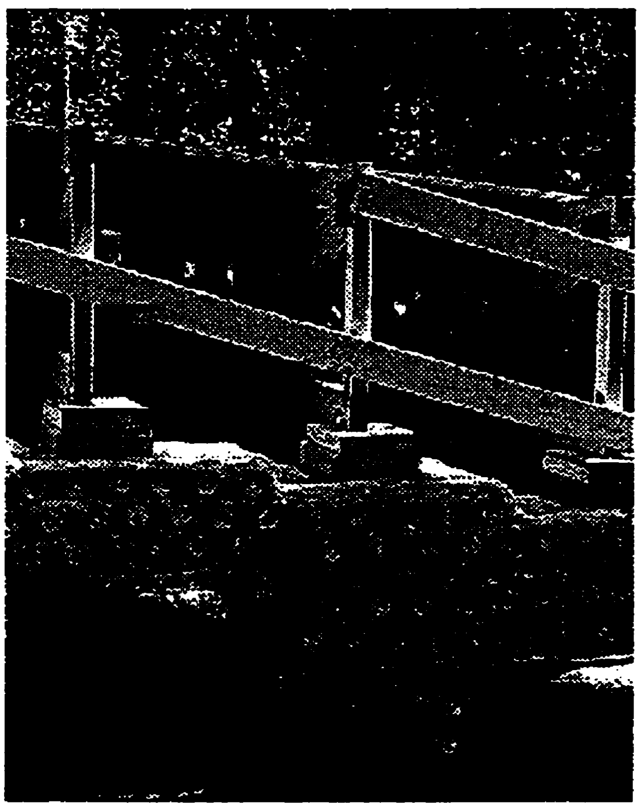


Figure 4.10 *- Tire House Roof Truss Support (Yellow Mountain, 1996)*

4. Concretes

Traditional cement based concretes have proved to be structurally and functionally adequate for building, however at a relatively higher cost. The higher costs are usually associated with concrete mix transportation and the local unavailability or high cost of cement and aggregate. As such, many alternative concrete type materials have been developed for use in home building. Cast earth has already been mentioned, but others include *aerated concrete*, *pumice-crete*, *cement/waste composites* and *cordwood*.

Aerated concretes are lime/flyash or cement/sand base mixtures combined with either preformed foam or a powered aluminum additive (those with the aluminum additive require high pressure steam curing). These combinations create a light weight and durable building material. *Pumice-crete* is also a low density concrete made from cement, water and pumice aggregate (sponge-like volcanic rock found in south-western United States) which combines to form a light weight, durable, fireproof and well insulating mixture (***Figures 4.11*** and ***4.12***). *Cement/waste composites* involve mixing cement with waste materials such as coir, jute, rice husk, wood shavings, saw dust or bamboo fibres (*Rao et.al., 1984*; *Jain, 1992*). *Cordwood* construction is a combination of short logs surrounded by a mortar mixture (***Figures 4.13*** and ***4.14***).

The main advantage of using these types of concretes is their use of locally available materials to create a relatively strong and durable material. Ease of construction varies for each material, therefore the design engineer should ensure the material chosen is compatible with the skills of local labour and the availability of equipment.

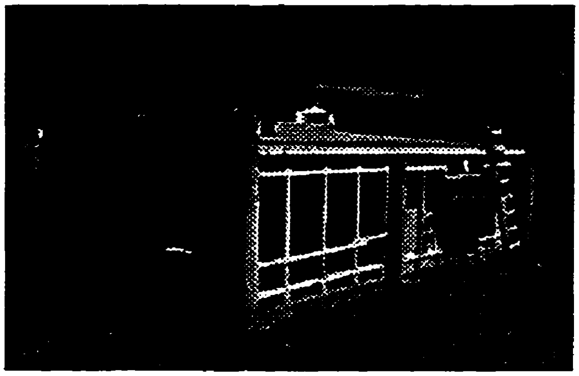


Figure 4.11 *- Pumice-crete Structure Under Construction (Pumice-crete, 1996)*

Figure 4.12 *- Finished Pumice-crete House (Pumice-crete, 1996)*

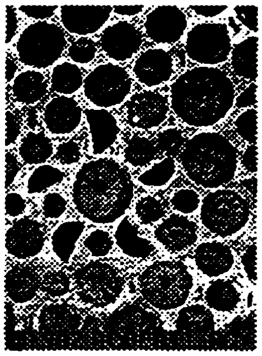


Figure 4.13 *- Cordwood Cross-section (Yellow Mountain, 1996)*

Figure 4.14 *- Cordwood Framing (Yellow Mountain, 1996)*

4.3 Environmental Design

Clever use of the natural environment may considerably reduce the costs and environmental impact of a house. For example, the sun is a source of large amounts of direct energy, mainly in the form of heat and light. Clever placement of high quality windows can provide much natural light and heat, thereby reducing the demand for electricity and non-renewable forms of energy currently being used to light and heat the common home (e.g., gas, oil). Solar energy can also be stored and converted to electrical energy via solar panels, which are commercially available and have become more efficient for home use. There are also natural ways to keep cool. Many homeowners are familiar with the cool temperature experienced when one enters the basement of a home. Even on the warmest of days, the temperature within underground rooms protected from direct sunlight remain surprisingly moderate.

Water usage is another important aspect of environmental design. The use of low-flush toilets and flow-limiting shower heads, for example, are two ways water usage may be significantly reduced in a new house (*Mattock and Rousseau, 1994*). Reducing water usage is environmentally favourable since it reduces demands on sewage and water supply systems (both natural and engineered municipal systems).

It is highly recommended that the engineer research past and current building efforts of the geographic location in question. This may provide valuable insight into what materials are available and their performance, what building technologies have not and have been successful, estimated building costs and ideas for new design innovations.

Some examples of complete housing systems which exploit the earth in a sustainable manner are demonstrated in the following examples:

1. Earthship

This impressive dwelling is constructed with tires, aluminum cans and earth (***Figure 4.15***). Power comes from the sun, water from the rain, and grey water and sewage are recycled on the premises. Homes of these specifications have been built by Mike Reynolds of Solar Survival Architecture, New Mexico. Depending on the level of involvement by the owner in the building process, construction costs have been reported to range from US\$70/ft^2 (full turnkey operation) to as little as \$11/ft^2 (for the do-it-yourselfer). But as Reynolds says, "Once the Earthship is built, it does not tax you or the planet" (see *Steuteville, 1995*).

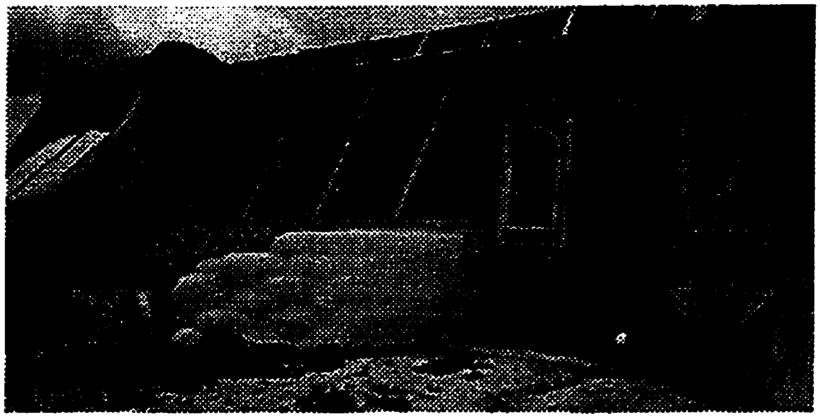
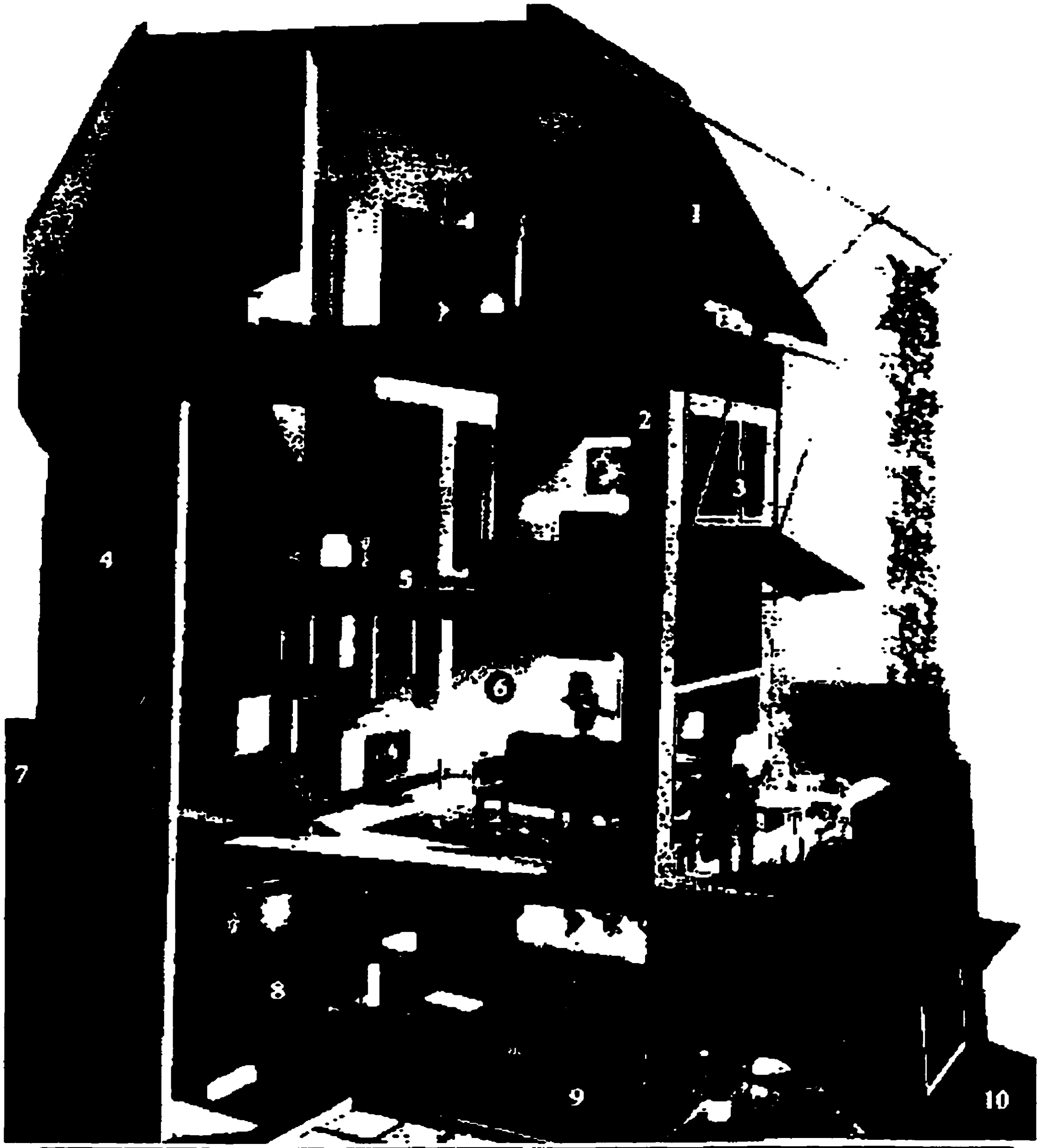


Figure 4.15 *- Earthship (Steuteville, 1996)*

2. Toronto Healthy House

Toronto, Canada is home to a similar project where a 1700 ft^2 home was built on an infill lot in the downtown area. The home utilizes solar panels to generate electricity, low-volume toilets and water faucets, non-toxic building materials where possible, a rainwater collection system and sewage treatment prior to discharge (***Figure 4.16***). The home requires no municipal service connections and total annual operating costs are approximated to be less than CN\$800/year (*Brennan, 1995*).



What makes It Work

1. Rooftop solar panels generate electric energy that can be stored for later use.
2. Airtight wall construction cuts heat loss, eliminates drafts and minimizes entry of moisture and pollutants.
3. Thermal windows are situated to provide natural light andpassive solar heat, cutting power and heating costs.
4. Building envelope has high levels of insulation to improve energy efficiency.
5. Low-volume toilets, low-flow shower heads and aerator faucets conserve water.
6. Materials used to furnish and decorate home emit few chemicals and vapors.
7. rainwater is collected, filtered, purified and stored for drinking and washing. It's recycled for use in appliances, toilet.
8. Wastewater from appliances and toilet filtered and treated before discharge.
9. First floor design ideal for home office. Working at home reduces need for transportation; reduction pollution.
10. Design appropriate for building on infill lots, promoting efficient use of land; reducing urban sprawl.

Figure 4.16 *- Toronto Healthy House (Brennan, 1995)*

4.4 Industrialization

Industrialization is a term used to describe a mass production assembly line approach to building. It involves large amounts of prefabrication which can range from housing components (e.g., doors and windows) to full housing systems (e.g., mobile homes) as well as coordination of the entire construction effort. The theoretical benefits of industrialization are:

a) decreased construction costs;
b) increased production (in terms of number of houses produced);
c) increased quality;
d) high technology capabilities in the midst of a shortage of skilled labour.

The idea for industrialized housing came about in the early 1900's, however it was after the destruction of World War II that many industrialized housing systems were designed and implemented. Europe experienced a much greater demand for housing at this time due to the complete devastation of many cities and the shortage of skilled labour; and therefore experienced greater growth in industrialized housing systems than the United States. In 1969, the United States government announced "Operation Breakthrough", which was a plan inviting industry professionals to submit industrialized housing proposals. The plan stressed high quality, high volume and cost efficient construction.

The developments in industrialization and prefabrication opened up possibilities for high quality, low cost, permanent dwellings that could be built to satisfy the great demand for shelter in all areas of the world. A truly noble vision indeed, however it is obvious from the current worldwide housing conditions (*Chapter 1*) that industrialized housing has not delivered. Some reasons contributing to this fact are as follows (*Vale, 1995*; *Shrivastav, 1974*; *Ural, 1980*):

a) Prefabrication usually involves high technology equipment and a factory setting. The capital costs associated with this can offset the cost savings of the prefabrication process and economies of scale of mass production; thereby resulting in actual higher costs than conventional construction.
b) Although the need for skilled labour is minimized, the need for skilled management is essential. The availability of skilled management has been a problem in attempts to implement industrialized systems, especially in developing countries.
c) Although the demand for housing is increasing, the construction industry is conducive to fluctuations and volatility. For an industrialized system to be successful, a steady market is required. The lack of an "aggregated market" and government support are two reported reasons for the failure of the Operation Breakthrough program in the United States.
d) Industrialized housing has also been known to be designed with disregard of the real needs of the people. Such projects can lead to mass rejection of the housing by the people and result in housing units left unused and growth in slum or squatter settlements.
e) Industrialization stresses quality, however an error in the prefabrication process may lead to consistent reoccurring error in a particular housing component, which could potentially lead to a consistent failure in the housing system.

Despite these facts, industrialization and prefabrication do have a place in the synthesis of a sustainable affordable housing project. *Partial industrialization* has become an accepted term which describes a reduced level of prefabrication from which a housing design can benefit. For example, a low technology, hand made clay brick production for low cost housing can benefit from the prefabrication of many bricks for subsequent use in many homes. Therefore, training a few individuals to produce bricks and providing them with a standard mold can result in many bricks being manufactured quicker than if the bricks were manufactured for each individual home separately. In developed countries, partial industrialization is evident in prefabricated engineered wood trusses for roofing. The trusses are factory assembled and delivered for on site erection.

Standardization is also an important component of industrialization which refers to establishing a dimensional uniformity in a housing component over an entire community development and/or geographic area. For example, the production of prefabricated doors may require a standard dimension of 850mm by 2100mm, whether exterior, interior and independent of the material used. This standardization can result in design and construction cost savings.

A final step to recognizing savings through industrialization is *modular design*. A modular design is constructed of standard dimensional modules that can be easily added or removed during the life of the house. Consider for example a 3m by 3m building module. ***Figure 4.17*** represents a modular house, with 36m^2 floor area, whereby 2 additional modules may be added as shown by the dotted lines. The potential advantage of this concept is that as the financial situation of a family improves, or the family grows larger, they can easily and affordably add to their dwelling. This can have positive financial implications for a newlywed couple who intend to start a family in the future, but their present financial situation does not allow them to purchase a dwelling of adequate size to handle the family expansion. This is of greater concern in developing countries where families do not have as much freedom to change the location of their habitat than those in developed areas.

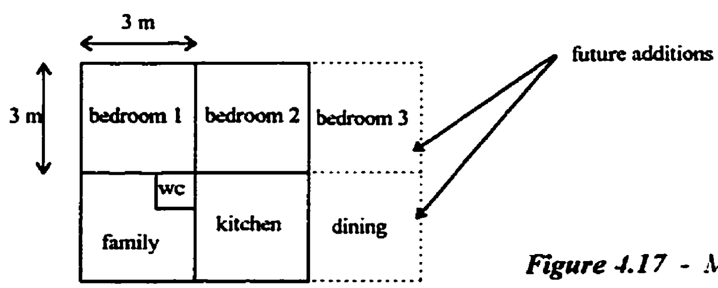


Figure 4.17 *- Modular Design Scenario*

4.5 Government Participation

The role of the government is to represent the people and provide a comfortable financial and social environment. The provision of adequate shelter falls into this realm of responsibility. The engineer must recognize that a sustainable affordable housing project will not succeed unless supported in principal by local government. Cooperation among all stakeholders is essential in systems design.

During design synthesis, the engineer should carefully consider the role the government will play in the project. Will there be financial support through subsidies or special lending provisions for homeowners? Is there or will there be environmental legislation in place which will constrain the design? What are the long term planning goals of the government and how will the synthesized design address it? As with climatic conditions, each geographic locale will carry a truly unique governmental situation to deal with. It is simply recommended that the engineer understand the role of the government within the context of sustainable affordable housing development and that a proper liaison is established.

4.6 Housing Components

Synthesis is the assembly of the physical parts that make up the housing system and requires a logical and systematic thought process. For example, investigation of the social and environmental conditions of an area will provide information such as target cost, expected physical housing attributes, materials available near the building site, and climatic data. The systematic thought process begins with this information, as demonstrated in the *Design Information* section of this report. The engineer must first create a conceptual image of what the exterior of the house should look like, how large it should be, how many rooms it should have, and other similar information. From this, the materials available which may be used to construct a house with the physical attributes desired need to be selected; bearing in mind general material life cycle considerations. Now structural aspects of design may be synthesized so that they satisfy the specified minimum standards. The combination of the material characteristics, established codes or standards, social expectations and climatic conditions will dictate the requirements of internal systems (e.g., heating and cooling). If the average outdoor temperature is 40°C, and occupants expect internal room temperatures to be maintained at 22°C, the insulating characteristics of the materials, in part, is needed to determine the cooling system requirements (i.e., what air conditioning unit will be able to maintain an indoor temperature of 22°C when the exterior temperature in 40°C?). One element of design depends on another and so on. At all times, the engineer should be mindful of the constraints to ensure that any alternative which violates a constraint is not carried forward to the evaluation procedure. Ultimately, the final design can be traced back to the information compiled by the engineer which describes the profile of the people, environment, climate, resources, economics and politics of the geographic area.

The design of complex civil engineering systems, such as housing, may benefit from considering separable *sub-systems*. The following sub-systems are recommended for general housing design:

a) *Walls*
   - interior load bearing
   - interior non-load bearing
   - exterior

b) *Floors*

c) *Roof / Ceiling*

d) *Openings*
   - doors
   - windows
   - skylights

e) *Foundation*

f) *Electrical*

g) *Plumbing*
  - includes toilets, sinks, etc.

h) *Heating / Ventilation / Air Conditioning*

i) *Interior Furnishings*
  - cabinets
  - stairs

j) *Exterior Furnishings*
  - stairs
  - deck / porch
  - driveway
  - pathways
  - fencing
  - railings

The desired end product of the design synthesis stage is a draft specification of each sub-system and their relative interactions (e.g., how the floor attaches to the walls). The specifications shall include detail sketches, a materials list and notes on the method of construction.

CHAPTER FIVE

EVALUATION AND OPTIMIZATION

Design synthesis provides the engineer with an opportunity to develop near optimum design alternatives based on an informed set of decisions. A housing model is the product of the design synthesis stage and is a physical description of the entire housing system. The description must include all aspects of planning, design, construction, operation and disposal of the home ***which shall serve as the source of information for evaluation***. Evaluation of the model represents a method by which the quantifiable parameters can be measured, and intangibles can be properly identified, so the degree to which the design meets the performance objectives can be determined. The following discussion presents a systems evaluation procedure for a sustainable affordable house.

5.1 Evaluation Criteria

The purpose of the evaluation criteria is to measure how well an alternatives meets the goals and objectives of a project. For sustainable affordable housing, it allows the design engineer to compare alternatives on a consistent basis resulting in the identification of one as a preferred alternative.

Objective 1 - Total Cost

Although any prospective homeowner would accept a house for free, there is a practical minimum cost associated with the building construction and operation. Therefore, a ***minimum*** total cost is what is practically desired. Evaluating total cost consists of a straight forward economic assessment of the total systems cost associated with a design alternative. That is, the costs of planning and design, construction, operating/maintenance and disposal are considered.

To address the systems lifetime costs in the economic analysis, *life cycle cost analysis* (LCC) is a very useful tool. A life cycle cost analysis considers the *time value of money*. For example, which scenario is more attractive: $1,000 offered now, or $1,000 five years from now? There is little debate that most people would accept the $1,000 immediately without much hesitation due to a variety of reasons; such as potential interest gains, or the risk associated with the uncertainty of waiting five years (will the money still be available?, will I still be here to collect?, etc.).

Specifically for housing evaluation, LCC is a handy tool for estimating the impact that time has on the completion of the project, for example, cost savings of completing a large project in two years versus four years. Another helpful use is evaluating long term economic performance of a house in terms of operating and maintenance costs.

To compare housing alternatives on an economically consistent basis, a *present value* is calculated, that is, <u>all</u> costs over the life of the system are represented as <u>one</u> value in present day dollars. For the evaluation of housing alternatives, two types of costs must be considered:

1. *One time future costs*

   A cost necessary once at a specific time in the future (e.g., exterior paint job).

2. *Annual costs*

   Equal costs required every year for the life of the system (e.g., electricity cost).

The following formulae may be used to reduce these costs to a present value:

a) *one time future cost* reduced to *present value*

$$PV = F \times \frac{1}{(1+r)^n} \qquad (1)$$

where: **PV** = present value
F = one time future cost
r = discount rate (decimal %)
n = the year from present future cost is made

b) *annual value* (A) reduced to *present value* (PV)

$$PV = A \times \frac{(1+r)^n - 1}{r\,(1+r)^n} \qquad (2)$$

where: **PV** = present value
A = annual expenditure
r = discount rate (decimal %)
n = number of years from present annual expenditure is made

Much discussion has revolved around the subjective process of choosing an appropriate discount rate. In general, the discount rate used for sustainable affordable housing evaluation will depend largely on the financial arrangements and stakeholders unique to the project. If uncertainty in choosing a representative discount rate exists, the design engineer should calculate life cycle costs using a range of discount rates and observe the sensitivity to the LCC outcome. For a detailed discussion on chosing discount rates and their application to risk assessment in LCC analysis, the reader is directed to the reference *Kirk and Dell'Isola, 1995*.

Consider the following illustrative LCC example where three housing alternatives are to be evaluated and compared in terms of total system cost.

For simplification, only five components for each housing system are evaluated (a fully modeled system would of course have many components to evaluate). The following chart summarizes the necessary LCC information:

Costs	**Alternative 1 (A1)**	**Alternative 2 (A2)**	**Alternative 3 (A3)**
construction	$105,000	$115,000	$100,000
heating/cooling	$2,000 / year	$1,500 / year	$2,500 / year
windows	replace: $3,000 useful life: 10 years salvage: $250	replace: $3,500 useful life: 15 years salvage: $300	replace: $5,000 useful life: 30 years salvage: $500
shingles	replace: $1,000 useful life: 15 years salvage: $50	replace: $500 useful life: 10 years salvage: $30	replace: $300 useful life: 6 years salvage: $20
system salvage value	$10,000	$9,000	7,000
design life	30 years	30 years	30 years
discount rate	5%	5%	5%

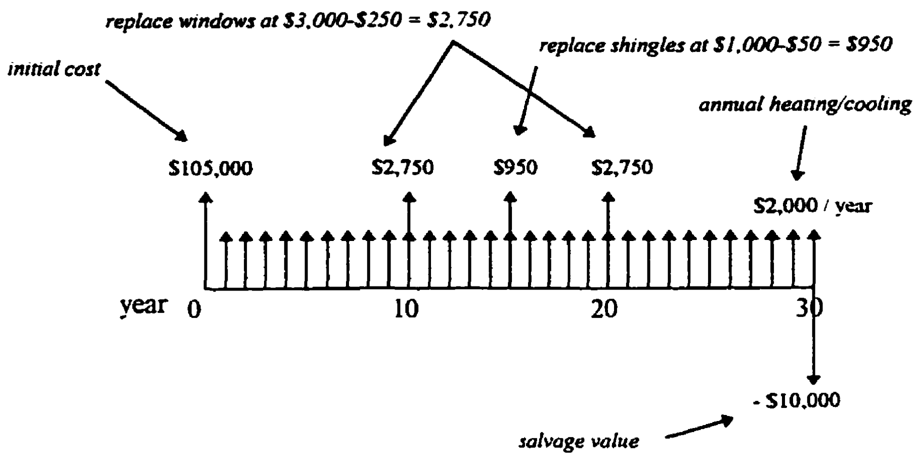
Analysis Period: 30 years
Discount Rate: 5%

For the windows and singles, a *replacement cost*, *useful life* and *salvage value* must be estimated. The salvage value accounts for the fact that the material is still worth something at the end of its useful life; as scrap or recyclable material. At the end of the useful life, the windows/shingles must be replaced at a cost equal to the replacement cost minus the salvage value. Alternatives must be compared over an equal *analysis period*, therefore if the design life is less than the analysis period, the cost for full disposal and replacement must be included in the analysis. Choice of the length of analysis period has less bearing than discount rate on the results of the LCC calculation in relative terms (in absolute terms, the longer the period analyzed, the greater the present value). In general, an analysis period of 20 to 50 years is reasonable for sustainable affordable housing.

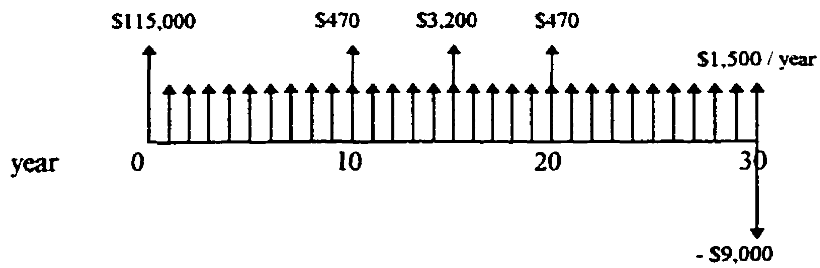
There is some degree of subjectivity inherent in the estimation of all these parameters, therefore as with the discount rate, if uncertainty exists, a range of values should be used and the sensitivity to the outcome observed. For simplicity, it is assumed that these values are satisfactory for the analysis of this situation.

Time lines summarizing these alternatives are as follows:

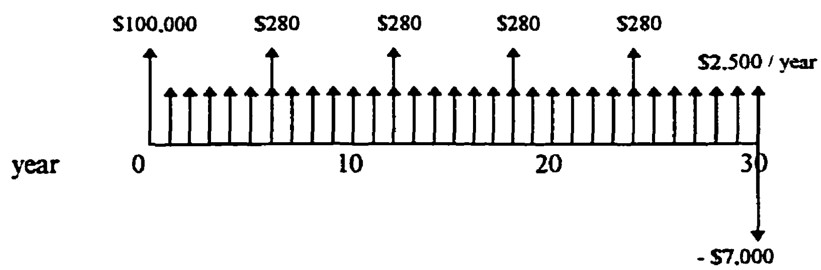
Alternative 1



Alternative 2



Alternative 3



Using equations (1) and (2) to reduce all cost to present values yields the following results:

PRESENT VALUE	A1	A2	A3
construction	$105,000	$115,000	$100,000
heating/cooling	30,745	23,059	38,431
windows	2,725	1,539	0
shingles	455	466	568
system salvage value	-2,314	-2,082	-1,620
TOTAL	$136,611	$137,982	$137,379

Therefore, although A3 cost least up front and requires no window replacement (i.e., windows last 30 years), LCC analysis reveals that the high frequency of shingle replacement (i.e., every 6 years) and low system salvage value result in a higher present value than A1. Also, the construction cost savings of A1 adequately offset the higher operating and maintenance costs, thereby making it the least expensive from a LCC perspective. A final ranking of alternatives is therefore: A1, A3, A2.

There are, however, some disadvantages with the LCC approach:

- Maintenance costs are the responsibility of the consumer upon purchase of the house, therefore a private sector designer/builder is usually only concerned with the initial construction costs (to maximize profit) therefore not considering LCC in design;

- LCC does not take into account changes in taste or fashion throughout the design life. For example, a certain colour of ceramic tile may be in style when the home is constructed, however after 10 years, the owner may wish to replace the tiles for reasons of aesthetics prior to the end of their useful life. These types of costs are difficult (if not impossible) to quantify.

- It is difficult to estimate future operating and maintenance costs since each homeowner will maintain their home to a different degree.

- Problems with estimating the discount rate are always present. Decreasing the discount rate tends to emphasize long term costs while using a larger discount rate tends to make future costs more worthless from a present value perspective. Changing the discount rate can affect the results of a LCC calculation. For example, when the above example is recalculated using a discount rate of 10% (as opposed to 5%), the following results are obtained:

Rank	**Total Cost**
A3	$123,491
A1	$124,977
A2	$129,641

- The result in the above table has occurred because the higher discount rate has given less priority to the future costs while emphasizing the upfront costs. Accordingly, the ranking of the alternatives reflects the magnitude of their initial construction costs.

With all these difficulties one may argue that LCC is less than perfect for evaluating the costs of sustainable affordable homes. This method, however, is extremely useful for comparing alternatives since it quantifies the tradeoffs associated with different design decisions on a consistent economic basis.

For the evaluation procedure of sustainable affordable housing, the following costs should be estimated and incorporated into an LCC analysis for each alternative:

a) *total planning and design costs estimated per dwelling*
   - cost incurred in gathering design information
   - total professional fees for preparing engineering drawings and specifications

b) *total construction costs per dwelling*
   - land purchase and preparation for construction
   - engineering services
   - labour
   - materials
   - equipment
   - management

c) *present value of operating costs*
   - heating/cooling
   - maintenance
   - repairs/upgrades
   - insurance

d) *present value of end of life disposal costs*
   - disassembly
   - recycling
   - disposal of non-recyclable/reusable materials

The values determined in a) and b) together account for the initial cost of the home (i.e., the cost passed to the consumer not including profit for the builder). It is this value that needs to be compared to the *target cost* calculated in the design synthesis stage to determine the degree of affordability of the housing alternative. The sum of all present value cost represents the total life cycle cost of the house.

Objective 2 - Environmental Impact

The total impact that a house imposes on the environment is of fundamental importance for achieving sustainability. As a result, there is need to quantify this impact and understand how it can be minimized in housing construction.

There are many aspects of the design, construction and operation of a house that contribute to its degree of environmental impact. First, the materials chosen for construction can have a significant impact which may be quantified by considering ***embodied energy***. Embodied energy is a relatively new concept in building science which is gaining popularity as the world slowly accepts the need for sustainable living. Exact definitions differ throughout the literature, however the following definition is appropriate; "***the energy required in the production and transportation of a building material measured in megajoules per unit***". Some definitions include the energy required for building construction and operation, however the evaluation procedure presented here shall consider these quantities separately (see below). Accepting the definition stated above, a material with a lower embodied energy is preferred.

How does one go about quantifying embodied energy? The non-renewable energy required in the transportation of a material can be estimated by fossil fuel usage of the transport medium. For example, the number of litres of diesel fuel burned by a transport truck to deliver a load of bricks from the manufacturing plant to the construction site can be converted into embodied energy by multiplying the quantity of fuel used by the "heating value" of the fuel expressed in megajoules per unit volume.

Quantifying the embodied energy resulting from the production process of a material is more difficult due to the numerous parameters involved. Current research is addressing this difficulty through the creation of databases of embodied energy for specific construction materials. As research efforts continue, the quantity and quality of this type of information will improve. The following table provides an example of recent data (*Mattock and Rousseau, 1994*):

VANCOUVER HEALTHY HOUSE PROJECT Embodied Energy Estimate Conventional Wall Section: 2 × 4 framing (per m^2)	
Material	**Energy Total (megajoules)**
Gypsum Board	60
Polyethylene Sheet	4
Kiln Dried Softwood	31
Fiberglass Batt	25
Oriented Strand Board	135
Asphalt Sheathing Paper	8
PVC Siding	215
Total	**478**

The above chart shows how a MJ/kg unit for a specific material may be converted into MJ by multiplying by the quantity weight of the material used in a particular part of a home (in this case, per m^2 of a 2 × 4 wall).

It shall be noted that when considering the entire housing system, materials used for temporary structures related to construction (e.g., retaining walls, site offices, etc.) should also be included in the embodied energy calculation.

A second important aspect in assessing the environmental impact is the non-renewable energy consumption required in the initial construction and annual operation of a house. The energy usage during the construction procedure is relatively simple to quantify. As a minimum, the calculation should include the sum of energy demands of machinery, power tools and temporary on site offices. Operating energy estimation procedures are well established in the industry and are often divided into the broad categories of heating, cooling, ventilation, lighting, domestic hot water and miscellaneous equipment loads (*Kirk and Dell'Isola, 1995*). It is anticipated that these categories should be sufficient for the majority of housing design alternatives. The values of construction and operating energy usage may be presented in *megajoules* (MJ) and *megajoules per year* (MJ/year), respectively.

Energy consumption alone does not reflect the entire environmental impact of a house. Many current materials used in housing emit or trap harmful substances which may result in serious adverse health effects (see *Chapter 4*). Favourable interior materials are those which are relatively inert and easy to keep clean, in addition to possessing a low embodied energy. A method of consistent quantification of the toxicity of materials is difficult since different materials will emit different substances and different design alternatives will have unique material combinations. One measure of indoor air quality is to perform an air quality test on the finished building and even then, there is question as to when the best time to perform the test is (i.e., what is the air quality versus time relationship?). For practical purposes of evaluating more than one housing alternative, it is recommended that a list of the materials being used which may be potentially harmful is created for each design. The specific use of this list shall be demonstrated in *section 5.3* of this thesis.

Additional measures of environmental impact include the amount of water usage within the home, measured in litres per year (l/year), and volume of waste produced during the construction process, measured in m^3.

Therefore, the following information related to environmental impact is required for the evaluation procedure:

a) total embodied energy of materials (MJ);
b) total energy required for construction (MJ);
c) annual energy required for operation (MJ/year);
d) list of potentially harmful materials and their health effects;
e) annual water usage (l/year);
f) amount of waste during the construction process (m^3).

Objective 3 - Social Acceptability

There is a largely intangible social aspect inherent in housing that must be evaluated. Due to the difficulty of quantifying these types of parameters, it is recommended that evaluation of the social criteria consists of a *subjective assessment of the physical attributes of the home and how these attributes meet the social expectations of the prospective homeowners*. Therefore, the social acceptability of sustainable affordable housing may be assessed by the following criteria:

a) *Functionality*
- Describe the physical aspects of the home (e.g., size, number and type of rooms, level of comfort, etc.) and any functional advantages or disadvantages of the design. Is the design compatible to the lifestyle of the people?

b) *Human Involvement*
- How well does the design incorporate the desired involvement of the prospective homeowners? This may be described in terms of the level of customizing choices offered; or the percentage of the home that is owner built.

c) *Familiarity with Materials and Technique*
- Are the materials used and physical design compatible with the people and surroundings? Is the design considered desirable by the prospective homeowners? This may require direct feedback for proper assessment via a community presentation, or perhaps a survey.

5.2 Multi-Objective Evaluation

There are many methods for the evaluation of engineering systems, one of the most popular being Cost Benefit Analysis (CBA). CBA is an economic analysis where all "costs" of the project are compared against the "benefits". Essentially, if the total economic value of the benefits exceed the total economic value of costs, the project is considered worthwhile. When multiple alternatives are being compared, the *preferred* alternative is the one with the highest benefit/cost ratio. Some positive aspects of CBA are:

- alternatives can be compared using a common economic unit;
- ranking of alternatives is possible;
- method is explicit and rational;
- it has a time dimension;
- based on well established economic theory (criterion of maximization and economic efficiency).

Many civil engineering designs, however involve parameters which are difficult to quantify economically (*intangibles*). The social aspect of housing is an obvious example. It is here that strict economical evaluation techniques begin to break down. CBA attempts to address societal values using *opportunity cost* (i.e., "the cost foregoing the opportunity to earn a return" - *White et.al., 1989*) and *willingness to pay* (i.e., the cost a person is willing to pay to realize a return; for example, the cost of a home security system may represent the economic value of the feeling of security).

A classic civil engineering system related example of valuing an intangible involves the value of a human life. Suppose a mining operation suffers an average of 5 deaths per year. Studies determine that if \$150,000 per year are spent to improve the safety of the operation, 2 lives per year can be saved. The question: "Is this proposal worthwhile?". This demands examining the deeper question of "What is the value of one human life?". Some would argue that there is no issue here, since human life is <u>invaluable</u>, the safety improvements should be undertaken without question. What if the safety upgrades cost \$500,000 per year; or perhaps \$1,000,000 per year? As inhumane as it may seem, there is always an upper limit (especially in this world run by economics), and at this limit exists an *implied* value on human life (e.g., undertaking the project at \$500,000 to save 2 lives would imply a value of \$250,000 per life). Now suppose this upper limit is dictated by a minimum expected profit level, that is, spending this extra money on safety cuts into the profit expectations of the mining operation. If the cost is great enough, the operation may not be economically feasible to continue, thus forcing a shut down of the operation leaving possibly hundreds of people without work. Suddenly, another scenario emerges: Is closing the operation and leaving hundreds unemployed worth saving the 5 lives lost per year under the normal operation?

Inevitably, the debate is virtually endless, and attempts to value human life have sparked obvious controversy. One such attempt suggests that a human life is worth the "earning potential" of that individual had he/she remained alive. In our mining example, if each miner earned $50,000/year, the total value of saving 2 lives would be $100,000 and therefore the safety improvements costing $150,000 per year would not be considered worthwhile. The "earning potential" value also suggests that the life of a professional earning say $100,000/year is worth more than the life of one of the miners in the above example (in fact, twice as much). This assertion creates obvious difficulties. Due to the difficulty of placing an economic value on a human life, virtually any price can be justified with enough propaganda. This leaves the evaluation procedure open to potential manipulation to achieve a desired result, thus reducing its credibility.

It is unreasonable from a practical perspective to attempt to place an economic value on an item which is inherently not economically quantifiable. Therefore, for sustainable affordable housing alternatives, it is necessary that a *multi-objective evaluation* procedure be implemented. Multi-objective evaluation, as the name suggests, involves evaluating more than one objective simultaneously. However, unlike cost benefit analysis, intangibles are not <u>required</u> to be reduced to a dollar value (or any other consistent unit). Recall one fundamental purpose of systems analysis; *to facilitate informed decision making.* Informed decision making is possible when all relevant information is gathered and assembled in an organized manner from which intelligent reasoning can be implemented. There are several established multi-objective methods which organize this information and apply a systematic framework to determine a preferred alternative (all from *Bishop et.al., 1976*):

a) *Visual Techniques*: social and environmental objectives are shaded to represent their relative desirability or undesirability on a series of map overlays. This technique is used mainly where "objectives and constraints have spatial significance".

b) *Rating and Ranking Methods*: a typical rating approach uses a +/- scale to indicate achievement of non-achievement; a ranking involves ordering alternatives from best to worst. Ranking has the disadvantage of not indicate the relative magnitude of how well a criteria meets the objective.

c) *Matrix and Linear Scoring Methods*: applies weights to each goal of an alternative and performs multiplicative and additive computations resulting in a single value. The advantages of this technique are the capability of assigning different levels of importance to individual criteria using a weighting system, and the use of a common unit that can be mathematically manipulated to achieve a single score (thus explicitly identifying a preferred alternative). However, determining accurate weights is highly subjective, which can severely affect the results, and assigning weights and scores implicitly values intangible parameters.

d) *Tradeoff Displays and Analysis*: organizes quantitative information in graphical or tabular form for tradeoff analysis. This technique also involves a high degree of subjectivity, however no direct attempt is made to quantify intangible parameters. Decision of the preferred alternative is made by careful examination of all available information.

e) *Multiobjective Programming*: computer algorithms based on mathematical optimization models. Can be accurate and simple to use, however the time required to develop the mathematical relations (not to mention the need to quantify all parameters) makes this technique more suited for mathematical optimization problems.

f) *Goals Evaluation Technique*: characterizes and compares impacts of alternatives based on the achievement of a systematic set of social goals. Although this technique is useful for social applications, the information requirements and the cost of the procedure can be quite high.

Characteristics of these evaluation methods are summarized in ***Figure 5.1***.

	Data Requirements	Analytical Complexity	Computational Effort	Public Participation Effort	Summary - Overall Cost of Application
Method	What quantity and quality of data are needed?	What is the level of analytical detail?	How much computer effort is needed for solutions?	What degree of public interaction is implied or needed?	What is the level of planning resource commitment?
I. Visual Techniques	limited to large* / "ball park"	graphical / aggregative	basic calculations / small to large* effort	none	low*
II. Rating and Ranking	limited / "ball park"	ordinal / aggregative	basic calculations / small effort	none	low
III. Matrix and Linear Scoring	moderate / "ball park"	numerical / aggregative	basic calculations / small effort	some	moderate
IV. Impact Tradeoff Analysis	moderate / precise	numerical / comprehensive	basic calculations / small effort	extensive	moderate
V. Multiobjective Programming					
A Objective Ordering	moderate to large / precise	math models / comprehensive	computer based / moderate effort	some	moderate - high
B Parametric	moderate to large / precise	math models / comprehensive	computer based / large effort	none	high
C Constraint	moderate to large / precise	math models / comprehensive	computer based / large effort	none	high
D Goal Programming	moderate to large / precise	math models / comprehensive	computer based / moderate effort	some	moderate - high
E Marginal Value Tradeoffs	moderate to large / precise	math models / comprehensive	computer based / moderate effort	extensive	high
VI. Goals Evaluation - Techcom	large / precise	math models / comprehensive	computer based / large effort	extensive	high

* Computer based techniques can involve large data requirements, computational effort and costs.

***Figure 5.1** - Characteristics of Multi-Objective Evaluation Methods (Bishop et.al., 1976)*

5.3 Preferred Alternative

The most important characteristic for a multi-objective evaluation procedure to embody, specifically for the comparison of sustainable affordable housing alternatives, is a *clear identification and display of the quantifiable and intangible tradeoffs among alternatives and their relative magnitudes.* Displaying this information in an explicit form promotes informed decision making and simplifies justification of the chosen preferred alternative. The evaluation criteria for cost and environmental impact are quantitative (except for *list of harmful products*), therefore a *linear scoring method* is recommended for evaluation of these criteria. However, social criteria, which cannot be ignored, are qualitative and may be treated using a form of *tradeoff display and analysis.* Therefore, a combined multi-objective method is recommended to evaluate sustainable affordable housing alternatives.

The following tasks are therefore required to complete the multi-objective evaluation procedure:

1. *Criteria Quantification/Identification Matrix*: This matrix displays the absolute values of the quantitative criteria and descriptors of the qualitative criteria. The purpose is to clearly display all parameters needed in the evaluation procedure.

2. *Linear Scoring*: Scores are calculated for the qualitative cost and environmental criteria and are summed to produced a total score for each alternative. The scores not only allow for a preliminary ranking of the alternatives, but also define a relative magnitude (i.e., *how much* better an alternative is over another). Since scores are summed across all quantitative criteria, relative weighting is required. For example, if a scores of 10 and 20 were summed to equal 30, it is implied that the criteria given a

score of 20 is valued exactly twice as much as the criteria given the score of 10. Determining relative weights which accurately reflect the conditions of the design location is very difficult, especially when considering criteria with differing units. If insufficient data exists to determine relative weights, it is suggested that the evaluation criteria of cost and environmental impact are equally weighted since they are both fundamental in determining the degree of sustainability and affordability. Within environmental impact, five quantitative criteria exist with which a relative weighting scheme must also be determined. It is recommended that embodied energy is weighted twice that of all other environmental criteria, as this is the most important factor in achieving environmental sustainability.

3. *Subjective Assessment and Justification*: The design engineer must subjectively judge the value of the relative qualitative tradeoffs among alternatives to determine whether they are substantial enough to cause a re-ranking of the alternatives (i.e., does the qualitative social benefit produced by one alternative over another outweigh the magnitude of the difference in score).

4. *Selection of Superior Alternative*: Based on the determined final ranking, a preferred alternative is identified.

This type of evaluation procedure has the disadvantage of not explicitly identifying the preferred alternative, however the extra effort involved in the subjective assessment and open forum created by clearly displaying the relative qualitative tradeoffs results in better accountability, and ultimately, better decisions. *The goal is selecting the alternative which is in the best interest of the stakeholders.*

5.4 System Optimization

Identifying one design as a preferred alternative does not imply that the design is optimum. Optimization means "best", therefore the following question is posed: "*How can the preferred alternative be made better?*" Making the alternative better requires that either the cost is reduced, the environmental impact is reduced, and/or the social acceptability is increased. That is, the performance objectives must become *maximized* or *minimized* to the greatest degree practically possible.

Although possible, it is not probable that the preferred design alternative will represent the absolute optimum solution. Optimization thus requires a two step process of *system analysis* and *re-evaluation*. System analysis involves carefully examining sub-system design to identify potential areas of improvement, which is followed by re-evaluation (which includes a re-quantification/identification of the evaluation criteria and subsequent multi-objective evaluation procedure) to determine if the change made does in fact result in an overall systems improvement. Optimization allows the designer to 'fine-tune' the design.

Inevitably, a design change which results in an improvement in a specific area of the design (e.g., reduction in cost) may produce an opposite effect on another aspect of design (e.g., increase in embodied energy). By subjecting the total system to a re-evaluation, the tradeoffs among the negative and positive effects of the single design change will be exposed. A design improvement is one which results in a total systems improvement.

As in any scientific experimental procedure, it is important that only one change is made with each re-evaluation. This allows for verification of a cause-effect relationship of the resulting improvement (or deterioration) in system performance. Hence the iterative nature of system optimization. Theoretically, a system is optimized when no further change resulting in a performance improvement can be made. Practically, it may be difficult to achieve this condition for sustainable affordable housing, therefore termination of the optimization procedure it is left to the discretion of the design engineer.

CHAPTER SIX

SAMPLE DESIGN PROCEDURE

The following example illustrates the systems design procedure for sustainable affordable housing. The information used is hypothetical, that is, it is not based real data from a specific geographic location. The purpose of this chapter is to demonstrate the systems design procedure proposed in this report and to identify potential decision making conflicts that may occur specifically with sustainable affordable housing design.

6.1 Design Introduction

Recall ***Figure 2.2*** - *Sustainable Affordable Housing Design Methodology*, the first three steps of the systems design procedure are to define project goals and objectives, and to collect background information. It has been stated (*Chapter 3*) that the goals and objectives for sustainable affordable housing are universal (i.e., *minimize cost*, *minimize environmental impact*, and *maximize social acceptability*) and thus shall be accepted for this example.

Once the minimum background information is collected (see *Section 3.2*), the relevant design information must be determined (*Section 3.3*). Following the procedure explained in *Section 3.3*, assume that a target cost of $50,000 has been determined. The physical attributes are described in ***Figure 6.2*** and minimum design standards have been determined.

Following the recommendations in *Chapter 4*, assume that three design alternatives which meet target cost (to be compared to "*initial construction*" cost in ***Figure 6.6***), contain the required physical attributes and satisfy the determined minimum standards have been synthesized. The three alternatives are described in ***Figures 6.3*** and ***6.5***. Due to uncertainty in choosing an appropriate discount rate a range of values shall be tested.

Figure 6.2 *- Physical Description*

Physical Attributes	**All Alternatives**
Rooms and Size	2 bedrooms 1 kitchen 1 family 1 bath full basement $36m^2$ total floor area
Amenities	hot/cold water electricity
Services	municipal sewers natural gas cable television
General	single storey detached 9m by 10m lot size

Figure 6.3 *- Sketches of Alternative Designs*

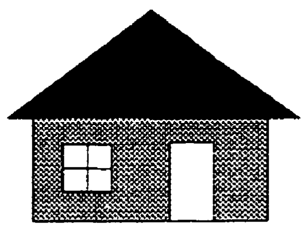
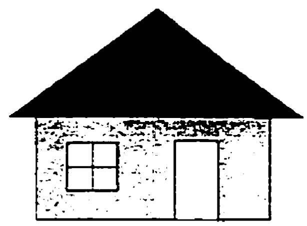
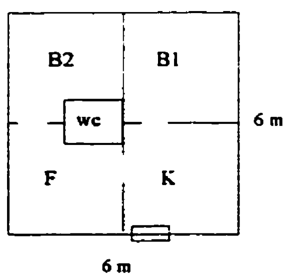
	Alternative 1	**Alternative 2**	**Alternative 3**
Front Elevation	traditional construction: wood frame with siding 	industrialized approach: pre-fab concrete panels 	indigenous materials: strawbale with stucco 
Floorplan		same	same

***Figure 6.4** - Construction Information*

	Alternative 1 *(traditional)*	**Alternative 2** *(industrialized)*	**Alternative 3** *(alternative)*
Walls (exterior)	siding sheathing plywood 2 by 4 studs @ 12" fiberglass batt vapour barrier gypsum board paint	pre-fab insulated interlocking concrete panels (modular capability)	stucco exterior 24" strawbale plaster interior paint
Walls (interior)	2 by 4 studs @ 16" gypsum board paint	pre-fab interlocking plastic/concrete panels	2 by 4 studs @ 16" gypsum board paint
Floors	2 by 10 joists @ 12" plywood tiles	2 by 10 joists @ 12" plywood tiles	tiles on concrete slab (see foundation) insulated
Roof / Ceiling	2 by 10 joists @ 12" flat with tar/gravel fiberglass batt drywall paint	pre-fab trusses shingles fiberglass batt drywall paint	thatch
Openings	1 wood exterior door 3 wood interior doors 4 wood frame windows	1 steel exterior door 3 wood interior doors 4 vinyl frame windows	1 wood exterior door 3 wood interior doors 4 wood frame windows
Foundation	basement 14" concrete strip footing concrete block sub drain waterproofing	basement pre-fab concrete panels sub drain	slab on grade with crawlspace
Electrical	standard	standard	standard
Plumbing	1 toilet 2 sinks tub	1 low volume toilet 2 sinks tub efficient shower head/faucets	1 toilet 2 sinks tub
HVAC	electric furnace no a/c	high efficiency gas no a/c	electric furnace no a/c
Interior	kitchen cabinets wood stairs to basement	kitchen cabinets wood stairs to basement	kitchen cabinets

Figure 6.5 *- Cost Information*

Costs	Alternative 1	Alternative 2	Alternative 3
Design	\$5,000	\$4,000	\$6,000
Land	\$10,000	\$10,000	\$10,000
Construction	\$35,000	\$35,000	\$20,000
Operating	\$2,000 / year	\$1,500 / year	\$2,000 / year
Disposal	\$4,000	\$4,000	\$2,000
Design Life	20 years	40 years	20 years
Discount Rate	2% to 10%	2% to 10%	2% to 10%
Analysis Period	40 years	40 years	40 years

6.2 Evaluation

The evaluation procedure must produce a *Criteria Quantification/Identification Matrix* which describes the alternatives in terms of all the evaluation criteria. Subsequently, linear scores for each of the quantitative criteria must be determined. Since it is desired that multiple discount rates be analyzed, this criteria is considered exclusively in ***Figure 6.6*** *(Cost Criteria Quantification Matrix)* which presents a summary of present value calculations and linear scores for the three alternatives over the discount rates of 4%, and 8%. ***Figure 6.7*** shows the relation between total present value and discount rate over the entire 2% to 10% range. ***Figure 6.8*** is a *Criteria Quantification/Identification Matrix* for the Environmental and Social criteria. The linear scores presented in the following tables are calculated as follows:

total present value:

A1 = \$102,901 A2 = \$77,856 A3 = \$83,385

total difference between worst and best alternatives:

\$102,901 - \$77,856 = \$25,045

therefore:

A2 receives top score of 60
A1 receives low score of 0
A3 receives pro-rated score of 47

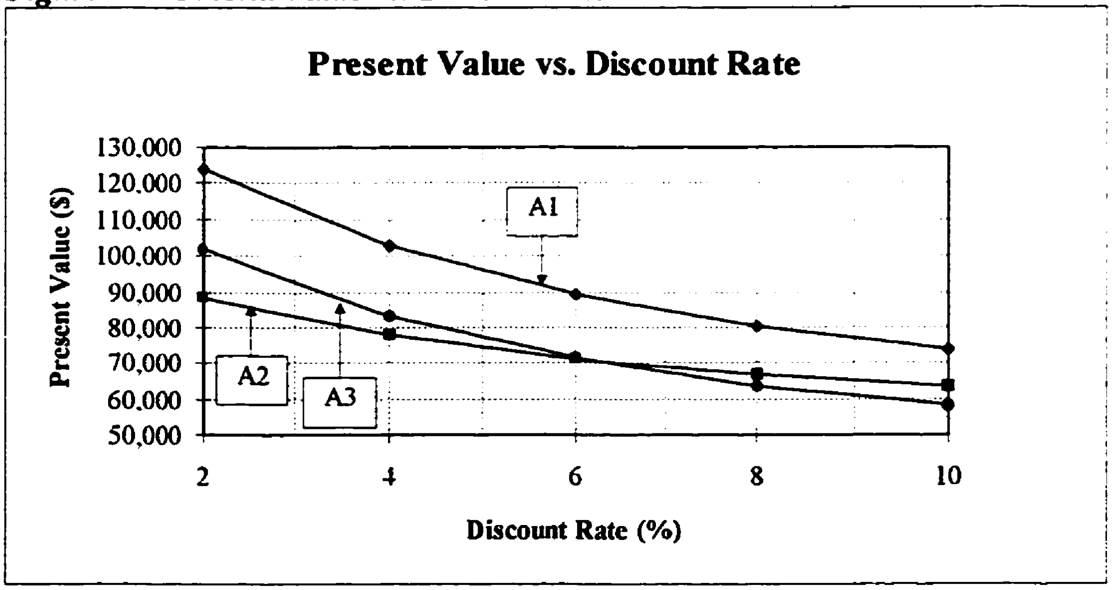
A3 score calculated as follows:

$$60 - \frac{(83{,}385-77{,}856)}{(25{,}045)} \times 60 = 46.75$$

Figure 6.6 - Summary of LCC

Criteria	Alternative 1	Alternative 2	Alternative 3
DISCOUNT RATE=4%			
Initial Construction Cost (design+construction+land)	$50,000	$49,000	$36,000
P.V. Operating Cost	$39,586	$29,689	$39,586
P.V. Disposal Cost	- $2,659	- $833	- $1,329
P.V. Replacement	$15,974	$0	$9,128
TOTAL P.V.:	**$102,901**	**$77,856**	**$83,385**
Linear Scores:	**0**	**60**	**47**
DISCOUNT RATE=8%			
Initial Construction Cost (design+construction+land)	$50,000	$49,000	$36,000
P.V. Operating Cost	$23,849	$17,887	$23,849
P.V. Disposal Cost	- $1,042	- $184	- $521
P.V. Replacement	$7,509	$0	$4,291
TOTAL P.V.:	**$80,316**	**$66,703**	**$63,619**
Linear Scores:	**0**	**49**	**60**

Figure 6.7 - Present Value vs. Discount Rate



An interesting result is discovered in this example. The superior alternative changes from A2 to A3 for discount rates greater than approximately 6%. Before any conclusions are drawn from this result, the quantitative environmental criteria should be analyzed.

In this example, it is assumed that the environmental criteria are equally important as the total present value cost. Therefore, to make the weighting of environmental impact equal to the weight of total present value cost, a high score of 60 must be used since four of the quantitative environmental criteria each require an equal score of 10, while it is recommended that embodied energy receive double the weight of the others (i.e., 20). Therefore, 4 * 10 + 20 = 60. A summary of the linear scores for the environmental criteria are presented in ***Figure 6.9***.

***Figure 6.8** - Criteria Quantification/Identification Matrix*

Criteria	Alternative 1	Alternative 2	Alternative 3
Environmental			
embodied energy	100,000 MJ	120,000 MJ	70,000 MJ
construction energy	5,000 MJ	6,000 MJ	3,000 MJ
operating energy	200,000 MJ/year	160,000 MJ/year	200,000 MJ/year
water usage	200,000 litres/year	150,000 litres/year	200,000 litres/year
construction waste	3 m^3	1 m^3	2 m^3
harmful products	• potential mold buildup with improper ventilation • paint fumes • microorganisms	• synthetic insulating materials may emit low levels of carcinogen • natural gas furnace potential CO source • microorganisms	• potential mold buildup with improper ventilation • paint fumes • microorganisms
Social			
functionality	• proposed floorplan is acceptable • reliable and durable design • full basement	• proposed floorplan is acceptable • very durable and efficient design • full basement	• proposed floorplan is acceptable • new low tech materials and technique, long term performance is uncertain • no livable basement area
human involvement	• homeowners are free to choose from a wide selection of interior and exterior colours • no changes in floorplan allowed • labour intensive design but no part can be owner built	• no choice of exterior or interior colours • no changes in floorplan allowed • industrialized and machinery intensive design	• homeowners are free to choose from a wide selection of interior and exterior colours • no changes in floorplan allowed • labour intensive design and some parts may be owner built
familiarity	• very familiar • widely used technique in area	• unfamiliar • widely used in other areas	• very unfamiliar • low incomes in the area may favour the possibility of lowering housing cost via self-build opportunity

Figure 6.9 - Linear Scores for Environmental Impact

	A1	A2	A3
Embodied Energy	12	0	20
Construction Energy	3	0	10
Operating Energy	0	10	0
Water Usage	0	10	0
Construction Waste	0	10	5
TOTALS	**15**	**30**	**35**

Combining the present value cost scores with the environmental impact scores produces the following total scores:

***Figure 6.10** - Total Score Summary*

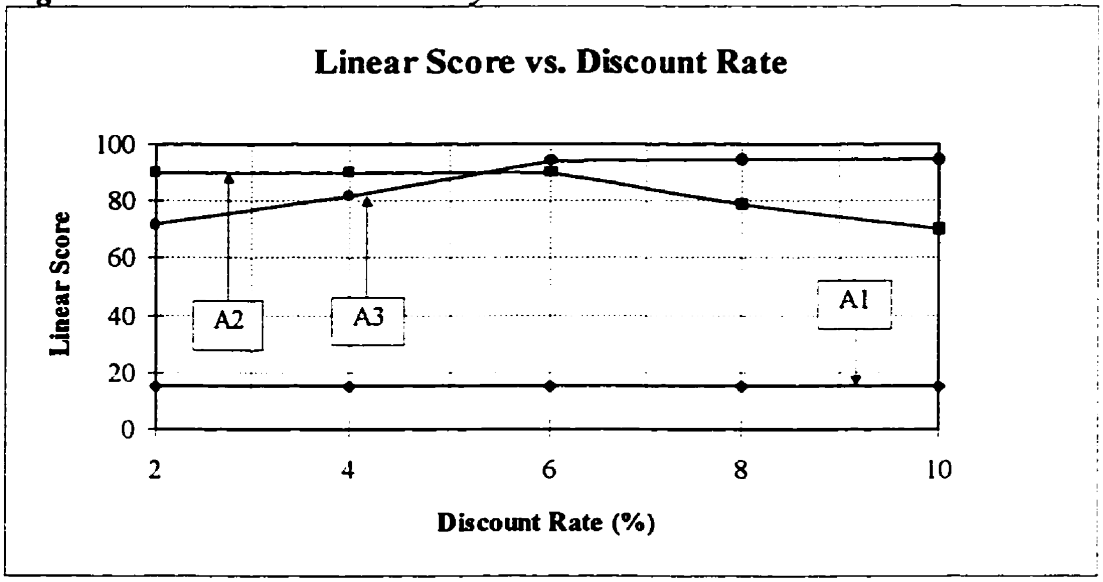


Figure 6.10 shows that when the criteria of cost and environment are combined, a change in rank occurs. A3 is superior to A2 only in the case when the discount rate is greater than approximately 5.3%. Once again, before a final decision can be made as to the preferred alternative, the social criteria must be examined.

Evaluating the social criteria is somewhat of an art. There is no doubt that the systems design procedure is a scientific problem solving approach, however most real life decisions require a degree of subjectivity. The systems approach cannot accurately determine a quantitative value for social criteria, as was seen with the example involving value of human life. What the systems approach does do however, is provide a tool for the decision maker by identifying important design parameters and relevant design information.

For sustainable affordable housing, subjective assessment of the qualitative criteria involves a thought process stimulated by the background information gathered which creates a discussion of the issues. A design situation in one geographic location may produce an entirely different result for identical alternative designs in another location. The circumstances unique to the area will dictate how the tradeoffs should be assessed. Bearing this in mind, the hypothetical discussion provided below represents one decision making scenario for the example presented in this chapter. The purpose of this discussion is to address some common issues which may arise.

The environmental concern of harmful products shows the potential for mold buildup and the presence of harmful paint fumes in A1 and A3 (***Figure 6.7***). Mold can be controlled with proper ventilation, and new home owners should be advised of proper procedures. Paints are of most concern early in the design life of the home. A2 produces no paint fumes from the prefabricated wall components, however materials used in the walls may emit carcinogenic products. There is little control over this, however, the true effects are uncertain since the materials and process are a relatively new construction procedure. The potential for CO emission from the gas furnace is of little concern since the gas furnace is based on a well established technology and a home CO detector is readily available to homeowners for a minimal cost. All alternatives show the potential for microorganisms, therefore this can be ignored for the purposes of comparing alternatives. Based on this discussion, A1 and A3 are considered very slightly superior to A2 due to the uncertainty associated with the carcinogenic content of the prefabricated walls.

Assessing the social criteria is somewhat difficult. When evaluating one alternative versus the others, it may be useful to consider all the information collectively and pose the following two questions, "What makes this alternative *better* than the others?", and "What makes this alternative *worse* than the others?" Answering these questions explicitly exposes the relative tradeoffs among alternatives.

Consider A1, it is superior to A2 and A3 in that it utilizes a construction technique and widely used and proven design which is very familiar to the prospective homeowners. No aspect of A1 is worse than both A2 and A3. Now consider A2, it is the most durable and efficient design. In a market which will welcome employment opportunities however, the machinery intensive construction procedure of A2 is a detriment, as is the unfamiliarity of the design. Lastly, A3 has a unique advantage in that prospective owners have the option of self-building part of their home, thus saving money off the purchase price. There is uncertainty with this approach however, since a minimum level of training needs to be provided despite the low technology materials and technique embodied by the A3 design. Also, A3 is not a proven design, is very unfamiliar and does not have a livable basement area. However, if the training can be provided, it would bring low cost homes to the community as well as promote the development of house building skills (a valuable commodity) to the local population.

A decision as to the preferred alternative must now be made. Although A1 is socially inferior to neither A2 nor A3, the very low relative score produced by the quantitative criteria make A1 an unlikely candidate for superiority. The social advantages simply do not justify the required increase in score.

Selecting between A2 and A3 in this example is difficult. Recall the scores and rankings indicated in ***Figure 6.10***. A3 becomes superior to A2 at discount rates above approximately 5.3%. The question of what is an acceptable discount rate is haunting this evaluation. By assuming the discount rate to account for inflation plus some level of social opportunity cost (see *Kirk and Dell'Isola, 1995*), an acceptable value is approximately 6% to 8%. Therefore, A3 looks slightly superior from a quantitative perspective. Socially, it is determined that the uncertainty in the A3 design is an undesirable risk, however the relatively low average income of the prospective homeowners, obtaining a home at the lowest possible cost is a priority as are the skills development promoted by the self build philosophy. With these priorities and considering all the background information and discussion presented above, A3 is considered the superior alternative.

6.3 Optimization

The optimization procedure can be a lengthy process where as many changes as is reasonably possible (i.e., from a cost and time standpoint) should be performed, therefore, optimization options for A3 will not be exhausted as part of this report. Optimization may proceed, however, by first considering the fundamental optimization question posed in *Chapter 5*, "*How can the preferred alternative be made better?*".

A3 showed minor inferiority to A1 in terms of construction waste and to A1 and A2 in terms of familiarity with design. These become the areas to target when optimizing the design. As previously mentioned, it is important that only one change be made prior to system re-evaluation. This will ensure that the observed change in performance, and its magnitude, can be solely attributed to the specific design change. Therefore, for this example, the design engineer should closely examine the design of specific housing components and perhaps investigate the possibility of some pre-assembly to help reduce on-site waste. In terms of familiarity, a change in architectural appearance or the type of finishes applied to the low-tech materials may help create a house more appealing and familiar to the prospective homeowners.

6.4 Other Engineering Applications

Civil engineering systems theory is a powerful decision making and analysis tool which can be successfully applied to the design of virtually any civil engineering system. This is true because every design process requires a the systematic solution of a set of questions, and multiple alternatives exist and should be considered in every design.

To demonstrate this versatility, consider the decisions involved in the design of a subway tunnel. The goal is to successfully provide subsurface access for a subway from one point to another. The objectives may be to minimize cost and minimize environmental impact. One major design decision involves the tunnelling method (e.g., tunnel boring machine, cut and cover, etc.). Determining the preferred method involves considering variables such as cost, time of construction, subsurface conditions and degree of disturbance to the surrounding area. For example, the high cost of a tunnel boring machine may be worth the reduction in tunnelling time and environmental disruption. Also, a preferred route must be chosen. Some routes may favour a specific tunnelling method; or even though it may be generally accepted that a shorter route results in a lower overall cost, perhaps tunnelling through an area with unusually difficult conditions (e.g., a concentration of boulders) would cause the cost of the tunnelling operation to be higher than if the route were lengthened and the difficult conditions were bypassed.

A more simple example involves the design of a slope for stability. The goal is a stable slope with the objective of achieving a desired factor of safety at the minimum cost (as an example). The factor of safety of a slope against failure is controlled by more than one factor (e.g., slope geometry, material properties, groundwater conditions, etc.). The engineer may be able to control certain factors such as the groundwater level (e.g., reduction through a de-watering program), or the angle of cut of the slope (i.e., addition or removal of material), and/or the use of engineered devices (e.g., soil anchors or geotextiles). Many combinations of one or more of these controls will result with the accepted factor of safety for stability. Optimizing this combination can be efficiently achieved using a systems approach.

CHAPTER SEVEN

CONCLUSIONS

This chapter concludes the thesis with a summary of the findings and a list of recommendations for future research in the area of sustainable affordable housing design and implementation.

7.1 Summary

The following points may be concluded from this research:

1. Current house building materials and techniques are contributing to environmental degradation and global population trends indicate an increasing demand for affordable homes. Therefore, providing an adequate supply of sustainable affordable housing is an area requiring research and initiative.

2. A systems approach promotes thoroughness and efficiency for the design of any civil engineering project. This type of holistic approach is well suited for sustainable affordable housing design.

3. The universal goals and objectives of any sustainable affordable housing project are to provide an adequate supply of homes at a minimum cost, with minimum environmental impact and maximum social acceptability. A design is geographically specific.

4. Although many building materials and techniques have been developed in recent years, a comprehensive database does not exist which may be used for quick and reliable reference when designing for a specific geographic locale.

5. Evaluation of sustainable affordable housing alternatives must clearly identify relative tradeoffs among alternatives. Quantitative criteria may be evaluating using a linear scoring technique, however social criteria must be assessed subjectively.

6. System optimization involves changing one specific design parameter and followed by a total systems re-evaluation to determine its effect. Unlike strict mathematical optimization procedures, sustainable affordable housing design optimization requires the design engineer to determine when the design is "optimum" and terminate the iterative procedure accordingly.

It may therefore be concluded that this research has provided valuable sustainable affordable housing design information by assessing current market conditions, identifying appropriate building materials and techniques, and providing a framework for the design procedure.

7.2 Recommendations

Based on the conclusions of this thesis, the following is recommended:

1. There is a need for a comprehensive database of sustainable affordable housing materials which may be used as a quick and reliable reference for design in any specific geographic locale. As a minimum, this database should include a measure of cost, embodied energy, geographic availability and an assessment of durability. This is by no means a simple undertaking, and requires extensive laboratory testing and consistent documentation procedures. In addition, periodic updates of such a database would be necessary.

2. As with any proposed scientific procedure, the systems design approach described in this report requires verification and refinement that can only be accomplished

through implementation. It is therefore strongly recommended that a specific geographic locale in need of housing be selected and a full systems design procedure is conducted to determine a suitable housing design. This will identify areas within the approach which require further development, that are missing, or are not necessary for achieving the desired product.

REFERENCES

Africa, 1985. "Tradegy of 'low cost' housing." Africa, No. 161, January, 1985. pp 35-36.

Bailey, R. 1993. Eco-Scam: The False Prophets of Ecological Apocalypse. St. Martin's Press.

Basu, A.R. 1988. Urban Squatter Housing in Third World. Mittal Publications. Delhi, India.

Bishop, A. et.al. 1976. *"Multiobjective Planning: Concepts and Methods."* ASCE Journal of the Water Resources Planning and Management Division, Vol. 102, No. WR2. November, 1976. pp. 239-253.

Brennan, P. 1995. *"Healthy House."* The Toronto Star. Toronto, Canada. December 2, 1995. pp H1/H6.

Cast Earth, 1997. *"A Revolutionary Innovation in Traditional Earth Construction."* http://lvnexus.net/nimud/cedesc.html#anchor212440.

Goodland, R. et al. 1994. *"Burden Sharing in the Transition to Environmental Sustainability."* Futures, 26(2), March 1994. pp 146-155.

Handa, V.K. 1989. *"Affordable Shelter - A Challenge."* Affordable Housing: A Challenge for Civil Engineers. Proceedings of a Conference sponsored by the Urban Planning and Development Division of the American Society of Civil Engineers. Miami, Florida. December 6-8, 1989. Edted by Ural, O and Shen, D. L. pp 67-75.

Houben, H. and Guillaud, H. 1994. Earth Construction. A Comprehensive Guide. Intermediate Technology Publications. London, UK.

Jain, A.K. 1992. Building Systems for Low Income Housing. Management Publishing Company. Dehra Dun, India.

Kaufman, M.T. 1989. *"Death of an Old Highway and a Home for the Homeless."* New York Times, New York. May 25, 1989. pp B1/B14.

Mafico, C.J. 1990. Urban Low Income Housing in Zimbabwe. Avebury. England.

Mattock, C. and Rousseau, D. 1994. "*Vancouver Healthy House Project Final Report*". Submitted to Canada Housing and Mortgage Corporation. January 5, 1994. By: Greg Johnson, Habitat Design and Consulting Ltd.

Meckler, M. 1996. Improving Indoor Air Quality Through Design, Operation and Maintenance. Fairmont Press Inc. Lilburn, USA.

Merritt, F.S. and Ambrose, J. 1990. Building Engineering and Systems Design. Van Nostrand Reinhold. New York, USA.

Nalder, I.A. 1991. "*Limits to Growth and the Message for Sustainable Development.*" Proceedings of the 1991 International Symposium on Technology and Society. Ryerson Polytechnical Institute, Toronto, Canada. June 21/22 1991. Editors: Burkhardt, H. and Vanderburg, W.H. pp 65-72.

Norton, J. 1997. "*A limitless myth.*" http://members.aol.com/jimn469897/limits.htm.

Population Referenece Bureau, 1997. "*1997 World Population Data Sheet.*" http://www.prb.org/prb/info/97wpds.htm#data.

Public Technology Inc., 1996. Sustainable Building Technical Manual. Green Building Design, Construction and Operations. Sponsored by U.S. Department of Energy, U.S. Environmental Protection Agency.

Pumice-crete, 1996. Pumice-crete Building Systems of New Mexico. http://www.taosnet.com/pumice-crete.

Ramamurthy, K.N. 1989. "*Shelter for the Homeless.*" Affordable Housing: A Challenge for Civil Engineers. Proceedings of a Conference sponsored by the Urban Planning and Development Division of the American Society of Civil Engineers. Miami, Florida. December 6-8, 1989. Edted by Ural, O and Shen, D. L. pp 76-84.

Rao, A.G.M. et al. 1984. Modern Trends in Housing in Developing Countries. E & F.N. Spon. New York, USA.

Sanera, M. and Shaw, J.S. 1996. Facts not Fear: A Parent's Guide to Teaching Children About the Environment. Regnery Publishing Inc.

Shrivastav, N.P. 1974. "*Low Cost Housing for Developing Areas through Partial Industrialization and Appropriate Technology.*" Master of Applied Science Thesis. University of Toronto. Toronto, Canada.

Steuteville, R. 1995. "*Earthships Ahoy!*" Learning for a Better World. http://www.betterworld.com/BWZ/9608/learn.htm.

Templeman, A.B. 1982. Civil Engineering Systems. The Macmillan Press Ltd. London, UK.

Toporow, C.M.C. 1991. "*Values Led Technologies.*" Proceedings of the 1991 International Symposium on Technology and Society. Ryerson Polytechnical Institute, Toronto, Canada. June 21/22 1991. Editors: Burkhardt, H. and Vanderburg, W.H. pp 228-235.

Ural, O. 1980. Construction of Lower Cost Housing. John Wiley & Sons. Toronto, Canada.

Vale, B. 1995. Prefabs. A History of the UK Temporary Housing Programme. E & F.N. Spon. London, UK.

White, J.A., et.al. 1989. Principles of Engineering Economic Analysis. Third Edition. John Wiley & Sons. Toronto, Canada.

Wilde, K. 1991. "*Economists and Engineers: Can we control this runaway team before they wreck our wagon?*" Proceedings of the 1991 International Symposium on Technology and Society. Ryerson Polytechnical Institute, Toronto, Canada. June 21/22 1991. Editors: Burkhardt, H. and Vanderburg, W.H. pp 41-48.

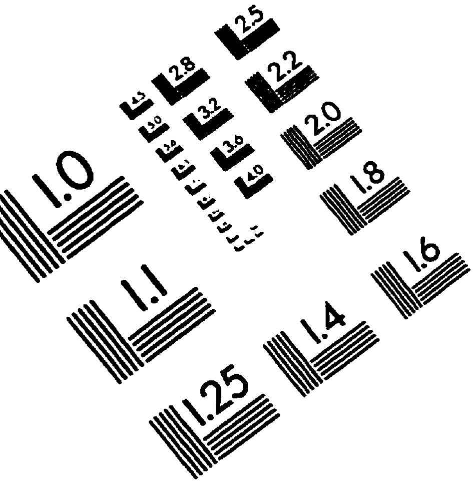
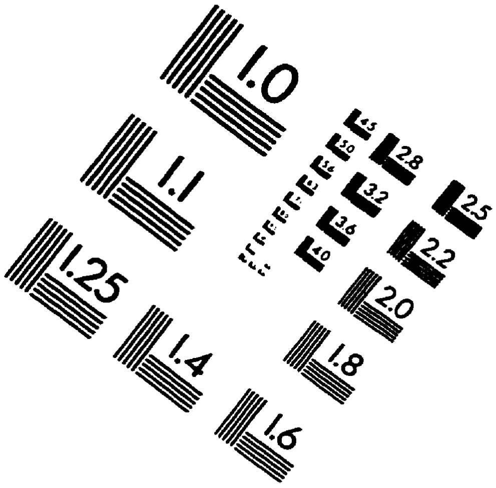
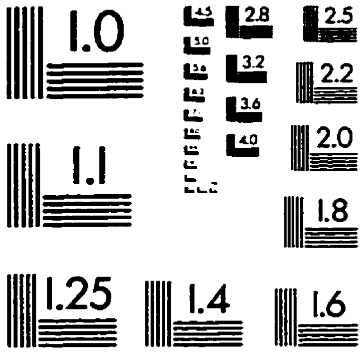
Wilson, A. 1995. "*Insulation Materials: Environmental Comparison*" http://www.ebuild.com/Archives/Features/Insulation?Insulation.html#RTFToC3 From: *Environmental Building News*, Volume 4, No. 1. Jan/Feb 1995.

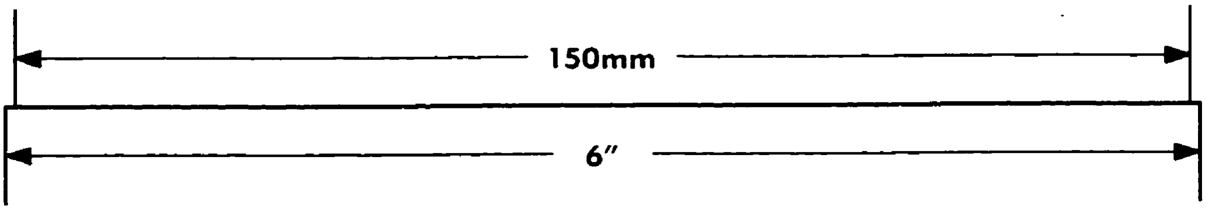
Yellow Mountain, 1996. Institute for Sustainable Living. http://monticello.avenue.gen.va.us/Community/Environ/YellowMtn.

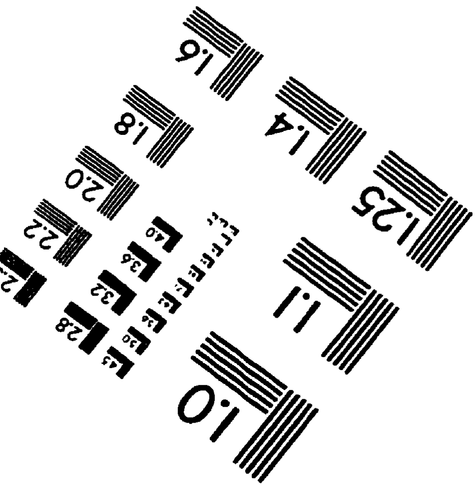
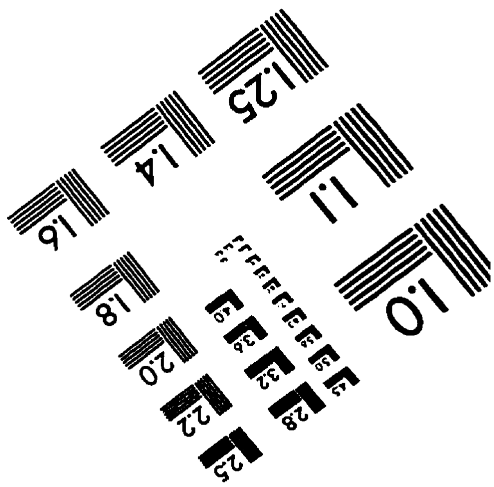
Young, S. 1991. "*The Materials Lifecycle Approach.*" Proceedings of the 1991 International Symposium on Technology and Society. Ryerson Polytechnical Institute, Toronto, Canada. June 21/22 1991. Editors: Burkhardt, H. and Vanderburg, W.H. pp 318-325.

Zarembka, A. 1990. Urban Housing Crisis. Greenwood Press. New York, USA.

IMAGE EVALUATION TEST TARGET (QA-3)



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