THE INFLUENCE OF DESIGN QUALITY ON PRODUCTIVITY IN CONSTRUCTION

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July 1994

ABSTRACT

In many countries, the productivity in the design office has been a neglected field compared with the outpourings of research and theory on productivity in construction. It may thus be useful to review the state of the art in construction research, as there are parallels to be drawn with the design environment. The author used ten construction projects to research the influence of design quality on the productivity in construction. The ten projects were all designed by the author. The data were collected after the construction phase and the direct costs were identified with rework(including redesign), repair, and replacement. Finally the author gives four equations for forecasting quality problems related to design in construction . The methods of analysis used are statistical, optimization, simulation and fuzzy logic.Analysis of the data indicates that in construction the deviations on projects accounted for an average of 12.4% of the total project cost. Furthermore, design deviation average 78% of the total number of deviations, 79% of the total deviation costs, and 9.5% of the total project cost. Since design cost is a small percentage of total costs, and an increase in design expenditure can frequently reduce total life cycle costs, it is important to research the influence of design quality on productivity in construction .

ACKNOWLEDGMENTS

The author wishes to thank the Faculty of Engineering and Applied Science of Memorial University for affording him the opportunity of conducting this work. Particularly, the supervision of Professor Dag A. Friis and his suggestion for an exciting research topic is greatly appreciated. The support and encouragement of Dr. J. J. Sharp , Associate Dean of the Faculty, Dr. Awad Hanna, the author's former supervisor are also acknowledged.

The author wishes to thank Mr. Michael J. Hogan , Mr. Lain G. Smith. They gave the author many beneficial ideas and practical support in the investigation and data collection.

The author is grateful to the Faculty of Engineering for financial support in the form of teaching assistantship and graduate support during his years of residence at Memorial University.

Finally, the patience and understanding of the author's wife and parents during the research and study period is greatly appreciated.

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CHAPTER 1. INTRODUCTION

1.1 The Challenge for the Canadian Construction Industry:

In Canada, the construction industry is a high proportion of total revenue income. It is roughly 8.3% of GNP, $50 billion-plus share of the Canadian gross national product. (Statistics Canada, 1988). This was also true in the Atlantic provinces and in Ontario. In Quebec, plant process design was as important as building projects and, in British Columbia the most important source of revenue came from projects related to agriculture, fisheries and forestry. In the prairie provinces, the dominant source of revenue was from oil, petroleum and natural gas projects at 36%.

The construction industry is the largest industry but the vast majority of its hundreds of participants are small businesses. According to Statistics Canada figures for 1988, over 90% of the 110,000 construction companies in Canada have twenty or fewer employees.

In design, of the 2513 architectural design firms in Canada, only 176 (8.17%) earned more than $1 million. The average firm in 1988 earned a fee income of $263,600 and had 5 employees. Forty-seven percent of the revenues ware earned by the largest sixty firms(1% of the total number of firms). (Statistics Canada, 1988).

In recent years, Canadian construction industry has faced many challenges. There are now, and will continue to be, shortages of resources, including materials, equipment, skilled workers, and technical and supervisory staff. At the project level, management has just begun to integrate design, procurement, and construction into one total process. There will be more and more governmental regulation on the safety of design and on field construction methods, environmental consequences of projects, and personnel policies at all levels. Management must also cope with new economic and cultural realities resulting from inflation, energy shortages, changing world development patterns, and new societal standards. But the greatest problem is that construction productivity improvement is very slow.

Canadian construction productivity has grown relatively slowly. Statistics Canada reported(1991) that from 1961 to 1988 , according to gross output multifactored productivity, average annual growth rates of construction productivity is 0.5% only. See Table 1-1 and Fig-1-1.

Table 1-1

Ranking of selected industries average annual growth rates (1961-1988)

(According to Gross Output Multifactors Productivity)

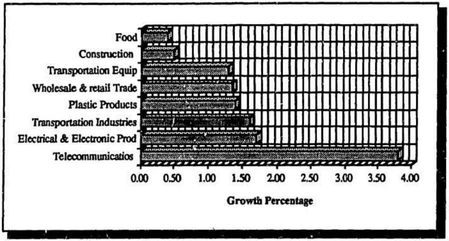
Industries	**Percentage**
Telecommunications	3.80
Electrical & Electronic Prod	1.70
Transportation Industries	1.60
Plastic Products	1.40
Wholesale & Retail Trade	1.35
Transportation Equip	1.30
Construction	**0.50**
Food	0.40

Source: Statistics Canada 1990-1991, Catalogue 12-204 E

Fig 1-1 Productivity Improvement of Different Industries

(Ranking Of Selected Industries According To Gross Output Multifactor Productivity , Average And Growth Rates)

(1961- 1988)



Compared with other developed countries, Canadian construction productivity grows slowly. See Table 1-2 :

Table 1-2 Construction Labor Productivity Comparison of Five Countries

COUNTRIES	PRODUCTIVITY
Italy	1.5
Japan	1.9
U.K.	2.9
Singapore	4.0
Canada	1.1

Source: J.K. Yates *International Labor Productivity* <<Cost Engineering >>Vol. 35/No. 1 Jan., 1993

From 1986 to 1990, Canadian construction productivity declined 3.7%,but construction labor unit cost increased 34.1% , see Table 1-3, and Fig 1-2

Table 1-3

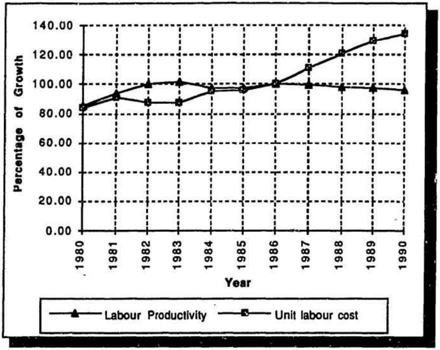
Canadian labor productivity and unit labor cost indicators

for construction industries

	Labor Productivity(Real GDP)		Compensation	Unit
year	Per person	Per personhour	Per personhour	labor cost
1980	85.50	83.30	69.80	83.80
1981	93.70	92.10	84.20	91.40
1982	100.10	104.00	91.30	87.80
1983	101.90	104.40	91.70	87.80
1984	97.50	98.30	93.40	95.00
1985	97.60	96.70	92.70	95.80
1986	100.00	100.00	100.00	100.00
1987	99.90	96.50	107.40	111.20
1988	98.40	94.10	113.60	120.80
1989	97.70	94.00	121.40	129.20
1990	96.30	95.40	127.90	134.10

(Source: Statistics Canada 1991)

Fig 1-2 Comparison of Construction Productivity and Cost



1.2 Improving Design Quality Is The Key To Increasing Construction Productivity

It is beyond the scope of this thesis to describe further the many problems facing the Canadian construction industry. From the writer's investigation of some construction sites and some design firms, we usually see the situation that labor blame the contractors; contractors blame labor and designers; and the owners blame them all. Too often, labor is made the scapegoat for poor design quality and poor construction management.

The reason for low construction and design productivity is the comparatively large numbers and small sizes of its businesses, its fragmentation and divisiveness, and its service characteristics. During economic recession, many construction companies, especially design offices have very limited time and resources available to allow them to study the reams of productivity data available, and develop a productivity program for their company. It is surprising that productivity improvements have not occurred in the Canadian construction industry. The vast majority of people involved in the industry do not know about the information which is available. This can also explain the lack of funding for productivity research in the construction industry compared with that of the manufacturing industry,(Price and Harris, 1985).

ASCE's (American Society of Civil Engineers) Hazardous Waste Liability Committee recently completed a survey of civil engineering firms practicing in the hazardous waste arena. The intent of the survey was to provide information on perceived liabilities in this field, and management tools to minimize those potential liabilities. The survey shows that about 30% of people think that Perceived Employee Liabilities depends highly on design, and 70% on construction management (Table 1-4 and Table 1-5). Furthermore, Diekmann (1985) investigated 427 construction projects, he pointed out: that the overall additive claim rate was 6% (i.e. six cents on the dollar) and , moreover, 72% of these increases were due to design error or owner initialed changes. From Yates's investigation, the design deviation cost is three times higher than construction cost in many countries. (J.K. Yates et. al. 1993). Therefore , to improve the quality of the design is the significant problem in the construction industry .

Table 1-4

Ranges of Perceived Corporate Liabilities

Technical category	Perceived Liability as Percentage of Respondents			
	Very low	Low	Average	High
Regulatory Interpretation	60	30	0	10
Field Assessment	30	20	50	0
Monitoring	30	30	30	10
Laboratory Analysis	65	20	15	0
Permitting	25	25	50	0
Preliminary Design	10	10	70	10
Final Design	10	30	20	40
Construction Management	15	0	15	70

(Source : Wayne Tusa, 1985)

Table 1-5 Ranges of Perceived Employee Liabilities

Type of personnel	Perceived Liability as Percentage of Respondents			
	Very low	Low	Average	High
Field	20	20	50	10
Lab	30	30	40	0
Design	10	0	60	30
Construction Management	0	0	0	100

(SOURCE: Wayne Tusa, 1985)

On the other hand , when owners discovered that design-construction and negotiated contracts in various forms could significantly reduce project duration, they intensified pressures on contractors to get facilities into production or occupancy at the earliest possible moment to maximize returns on invested capital. Construction was increasingly programmed to proceed simultaneously with design in the industrial and building fields. From Table 1-6 we can see that in pure additive claims, design errors account for 39% of total claims. In pure deductive claims, Value Engineering (mainly depends on design) accounts for 63% of the deductions. (Value Engineering is a systematic approach to obtaining optimum value for every dollar spent).

TABLE 1-6 **Contract Adjustments by Claim Type**

Claim type	PURE ADDITIVE CLAIMS								PURE DEDUCTIVE CLAIMS			
	Total Claims		Claims		Compensation		Time Extension		Claims		Deduction	
	Number	%	Number	%	Dollars 1000's	%	Days	%	Number	%	Dollars 1000's	%
Design errors	166	39	145	46	2452	40	290	18	14	29	38	10
Changes Discretion	72	17	40	13	1042	17	135	9	45	10	12	3
Mandatory	55	13	41	13	662	11	55	3	14	29	92	24
Differing site conditions	65	15	46	15	772	13	140	9	0	0	0	0
Weather	29	7	29	9	0	0	560	35	0	0	0	0
Value engineering	16	4	0	0	0	0	0	0	15	32	240	63
strike	5	1	5	2	0	0	400	25	0	0	0	0
Other	19	4	7	2	1202	19	3	0	0	0	0	0
Totals	427	100	313	100	6130	100	1583	100	48	100	382	100

Source from : James E. Diekmann 1985

Historically speaking, productivity of employees is a major concern in all construction organizations. The optimization of the production of the total organization can be achieved through the coordinated improvement of the performance of the individual employees. For many years the productivity of blue collar workers in the construction industry has been studied and evaluated. However, several studies have revealed that poor management was the cause for poor worker productivity . This indicates that attention is also needed to improve the productivity of "white cellar" employees in construction.

Improving design quality is the process of increasing design productivity. Sometimes it can be thought of as a design management problem. It should be widely included in the construction management field both in Canada and other countries. Productivity in the design office has been a neglected field compared with the outpourings of research on productivity in construction or manufacturing activities. So it may be useful to review the state of the art in construction research. There are parallels that can be drawn with the design environment. What needs to be said at the outset, however, is that productivity gains in the design office will not come as easily as those on the construction site. This is because production of engineering designs consist of a large number of complex, vague ideas, interdependent tasks, which are not easily measured and flowcharted .

1.3 Research Objective

The research presented in this thesis was conducted to identify the causes and magnitude of quality problems in design and construction and to determine the costs associated with the quality problems. The author will use statistics and a fuzzy logical method to analyze the influence of design during construction. The degree of complexity is used to consider some problems of design and construction. Finally, the author will give four regression equations for forecasting design and construction deviations and man-hours in practice. The research was conducted under the guidance of the Canadian Construction Code and Chinese Construction Code.

1.4 Data Collection and Research Methodology:

In order to quantify some of the factors that affect design and construction productivity, the productivity data was collected by this author. It includes two parts. The first part are ten real construction projects. The author designed these in the past ten years in China. Most of the practical problems were directly faced by the author. The second part is , in St. John's Newfoundland . The author visited some design firms, and visited two construction sites on a daily basis and collected both quantitative and qualitative data. The data were collected over two periods, one is 60 days (C-Core Laboratory), another is 90 days (General Hospital Cancer Center). Different countries' construction codes are different. However, the principles on which they are based are very similar. Because of the differences in construction code and availability of completion date, just the following ten projects (Table 1-7) are used in subsequent analysis.

The name of the projects of the Table 1-7 is as following:

A. Beijing People's Broadcasting Station.

B. Huabei Hospital

C. Japanese CANON Factory Workshop

D Beijing Normal University classroom Building

E. Chinese International Investment Company Building

F.Japanese TOSHIBA Factory

G.Beijing Eleventh Asian Games Sportsman House

H. Gaojaiayun District

I. ZhongShan Building

J. Jinan Supermarket

TABLE 1-7. Descriptions of Projects Studies

PROJECT	TYPE OF STRUCTURE	TYPE OF USE	TOTAL INSTALLED PROJECT COST(RMB)
A	Concrete Frame	TECHNICAL	90,000,000
B	Concrete Frame	HOSPITAL	20,000,000
C	Concrete Frame	WORKSHOP	30,000,000
D	Steel Structure	RESIDENTIAL	12,500,000
E	Steel Structure	OFFICE	234,000,000
F	Steel Structure	FACTORY	19,000,000
G	Masonry Structure	RESIDENTIAL	7,500,000
H	Masonry Structure	RESIDENTIAL	10,900,000
I	Masonry Structure	HOTEL	65,000,000
J	Flat-Plate	COMMERCIAL	76,900,000

{Note : 100 Canadian Dollars = 635 RMB, in 1994 exchange rate}

Some information was also obtained from interviews with contractors not associated with the study sites. The main focus of the data collection was on the measurement of work completed by the design and construction including concrete frames, steel structures, masonry structures, plus masonry crew and the factors which affected their productivity. The observer completed a simple data sheet every day which served as a guide for the data collection process. Some of the environmental data included temperature, wind speed, humidity, and precipitation readings. The weather information recorded on site was supplemented with weather data published from the St. John's weather office for the region. (The information of the ten Chinese projects did not include weather conditions). There were measurements of the amount of block and brick work completed during the day as well as the crew sizes and working hours. The size and type of materials used were considered important to the study and were also collected. Any absentees, overtime, or accidents were recorded . The qualitative data came from the observers own observations of the work, from informal discussions with the crews, and from interviews with the site foremen. The purpose of obtaining qualitative data was to identify any significant problems, delays , interruptions, or disruptions which occurred during the shift. A disruption is defined as "an event occurring on-site that adversely affects the crews productivity for most of the workday" (Sanders and Tomas, 1991).

The observer could not stay on the construction site throughout the entire shift which meant that much of the information regarding delays, and daily progress, depended upon informal discussions with site personnel. The information obtained often depended on who the observer interviewed and on their evaluation of the incident. Sometimes details of the incidents may have been omitted. The quality of information improved as personal rapport with site personnel improved. Cooperation from site management was essential for the data collection process. Hence, creating a good working relation with them was imperative. To maintain this relation, it was important for the observer to direct inquires to management at times when they were not busy with job related activities. When questions were held for less busy times the information received was more in depth and well thought out. The management personnel from the general contractor were quite willing to help in the study, and eager despite some initial skepticism. The crews, subcontractors , and foremen also cooperated.

The objective of the data collection was to identify and quantify as many factors as possible that affected design and construction productivity. The reason for this is that there are so many factors that simultaneously affect productivity, it is almost impossible to unravel them and determine their individual effects during a study of this size. To even come close to creating a model which can accurately predict the productivity that will be obtained during a shift, would require considerable additional research. It was deemed more beneficial for this study to try and make everyone in the industry more aware of the major causes of productivity losses during design and construction projects, especially the relationship between them. This way one can try to take steps to eliminate the negative factors.

It was not possible to get sufficient data on the design related aspects of the two Canadian projects to get a quantitative indication of the differences between Canadian and Chinese construction and design environments. The Canadian data has therefore been omitted since it will not add sufficient information to give any additional insight into the problem area studied. It is mentioned here, only because considerable time and effort was spent in trying to get enough information to make a meaningful comparison between Canadian and Chinese practice. Unfortunately this effort failed.

In quantitative analysis, the author used fuzzy logic, optimization theory and statistical methods.

CHAPTER 2. THE CONSTRUCTION MANAGEMENT AND HISTORY

Before studying the influence of design in construction, we should know something about construction management and its history. Management is critical in improving productivity in both the design and construction processes.

2.1 Management

Usually we define management as the use of people and other resources to accomplish objectives. This definition is applicable to all organizational structures, both profit-oriented and not-for-profit. (Boone and Kurtz 1992)

Management involves the creation of an environment in which people can most effectively use other resources to reach stated goals. It involves the implementation of four basic functions: planning, organizing, leading, and controlling. These functions play a role in the operation of all organizations.

Construction is the process whereby the designer's plans and specifications are converted into physical structures and facilities. It involves the organization and coordination of all the resources for the project (labor, construction equipment, permanent and temporary materials, supplies and utilities, money, technology and methods, and time) to complete the project on schedule, within the budget, and according to the standards of quality and performance specified by the designer.

2.2 Construction Management History

Historically speaking, construction management and productivity of the construction site (or the factory floor) has been a focus of concern since at least the time of F.W. Taylor, when his theories of "Scientific Management" first drew attention to the fact that there were better ways of doing many things than the traditional way. Indeed, it was Taylor's contention that no field of activity , no matter how simple, could not be improved by the application of scientific management , and to support this view he used his famous example of the pig-iron handler. So well known did this example become, that Taylor was later to lament that "people seem to think that the whole of scientific management consists in handling pig-iron" (Taylor 1947). As is the fate of many theories, Taylor is currently unfashionable, and it is nowadays common to pour scorn on scientific management. There are good reasons for this. Taylor appears to have had little respect for the intelligence or humanity of his workers, and treated them as purely production units. But, it should not be forgotten that scientific management can lay claim to some significant achievements. Its methodology lives on under the general title of "methods improvement" studies. The modern version is more acceptable in that it also takes account of the fact that tasks are carried out by people, who have their own needs and are motivated for good performance in different ways. This can be attributed to the work of the "Human Relations" school of management theories. The work of this school (Mayo 1949; McGregor 1960; Herzberg 1966) also owes a debt to scientific management, in that it arose chiefly to oppose the perceived heartlessness of scientific management.

The past realities of construction management will now be examined as well as the realities of today. The following descriptions from a designer viewpoint, outline major differences among approaches and explore some of their variations, advantages, and disadvantages, as well as their similarities.

(1).Traditional services in the 1950s

Here the owner employs a designer (architect, architect/engineer, or engineer) who first prepares the plans and specifications, then exercises some degree of inspection, monitoring , or control during construction. Construction itself is the responsibility of a single general contractor under contract to the owner. Much of the work may actually be performed by individual trade constructors under subcontract to the general contractor.

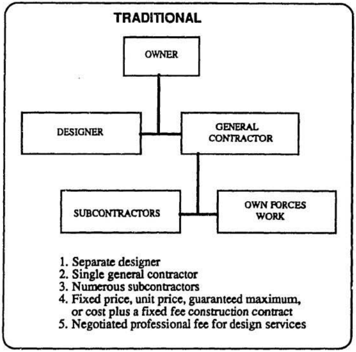


Fig 2-1 Traditional Service

The traditional approach was a sequential, linear flow of preliminary design, construction documents, and supervision of construction. Codes and zoning laws were not too complex for the most part, and the time for zoning and other public approvals of a project was usually predictable, routine, and short. Relations between architect/engineer and client and architect/engineer and contractor were stable, and the idea of errors-and-omissions insurance had not yet been born. Construction costs could be reasonably projected using the cost-per-square-foot method. Cost consultants were few and far between. As the pace of construction quickened and the volume and complexity of buildings grew, the old traditional ways of service did not fit the needs of the times.

(2).Comprehensive Services of the 1960's(The Owner Builder)

In the decade construction projects became larger. Large projects became multibuilding projects. New towns were designed and built, city planning grew into regional planning. More engineering systems made buildings more complex and difficult to supervise during construction. The standard form of architects/engineers agreements was changed; architects/engineers observed construction, they no longer supervised it. Errors-and-omissions insurance was invented, and with this protection came exposure, and the number of suits expanded again. Relations between architects/engineers and contractors were not as well coordinated as they had been during the fifties. With the growth it followed that time required for receipt of public approvals was longer in the sixties than in the fifties.

Therefore, many city, and county public works departments and private companies have performed both their own design work and some or all of the actual construction with their own forces to meet this challenge. This approach is often referred to as "force account." Other owners (or owners' representatives), while retaining many of the management and conceptual design responsibilities, have utilized consultants for some or all of the detailed design, and have depended upon construction contractors for the actual hiring and supervision of the labor force.

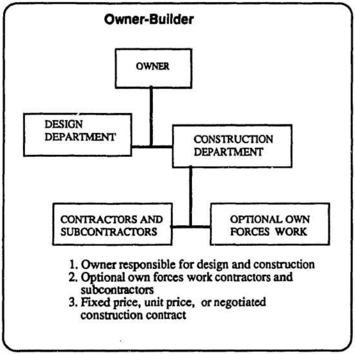


Fig 2-2 Owner - Builder Service

Owner -builders have utilized many of the contractual forms discussed above for the traditional approach, and they are increasingly moving to professional construction management methods. Actually, the owner-builder can be likened to the design-constructor, except that the ultimate product is utilized in-house rather than developed for an outside owner. Many of the owner-builders have developed design-construct divisions that are of a size comparable with those of many of the larger turn-key builders. However, it appears that this method of work is relatively large and relatively constant over a long period of time, and where project management can be separated from operational management.

The owner-builder can employ all the techniques of the design-contractor, the professional construction manager, and the traditional approach. However at present the advantages of this type of approach are best suited to a relatively few, favorable situated companies or agencies now.

(3).Fast-Track Service in 1970's. [Design-Construct or Design-Manage(Turn-key)]

The fast-track method is organized to reduce the time needed for construction, making possible earlier occupancy and reducing financing costs. In fast-track, as soon as the schematic design is accepted and public approvals are received, the construction manager (who sometimes is the architect) breaks the project down into a series of phased bid packages. Work in the field can be started immediately, and materials and equipment requiring long lead time are ordered. Final design and documentation, for separate billed packages, continue until the building is completed.

During this decade a swarm of package builders and others invaded the design professional's field and offered owners a design-build package. Architects and engineers countered by getting into the development business themselves. They organized joint ventures and consortiums in any number of ways that might be attractive to clients. Design-build uses the fast track method of construction, but it does so at a fixed price and with a single responsibility. Architects supply services to the point of single responsibility and not to the owner, and great care is needed to avoid conflicts of interest.

Some authorities differentiate between "design-construct" and "turnkey." General usage, however, treats them interchangeable. In this method, all phases of a project, from concept through design and construction are handled by the same organization.(Fig 2-3)

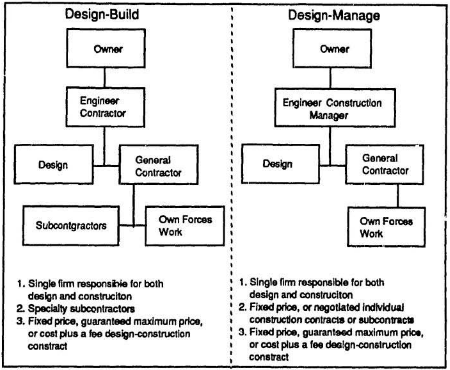


Fig 2-3 Turn-key Organization

In the case of design-constructor, the constructor acts as a general contractor with single-firm control of all subcontractors. Usually, but not always , there is some form of negotiated contract between design-constructor and owner. In the case of design-manage, construction is premed by a number of independent contractors in a manner similar to the professional construction management concept. Under either design-construct or design-manage, construction can readily be performed under a phased construction program to minimize project duration. This form of completing projects has been used for the majority of process-oriented heavy industrial projects constructed in the United States in the last few decade. Reference to Engineering News-Record's (ENR) annual list of the

500 largest designers show that the design - constructors are heavily represented in the top 20.

(4). Impact analysis and design services in the 1980s.

(Professional Construction Management)

In the eighties , all patterns of construction management continue to be used. The traditional linear form continue in use for smaller projects. The trend is clear, however. New methods has been found to shorten construction time, and increase the productivity of designer and constructor. That is Professional construction management.

Professional construction management involves a three-party team of owner, designer and construction manager in a non-adversary relationship, and it provides the owner with an opportunity to participate fully in the construction process. Its success depends upon elimination of adversarial relationships among team members. Should one or more of the team members introduce concepts or policies detrimental to naturally satisfactory relationships, the concept deteriorates into an adversarial situation, with inevitable negative effects upon both the project and individual participants. Barrie gave a clear picture for Professional construction management (Barrie 1992), see Fig 2-4.

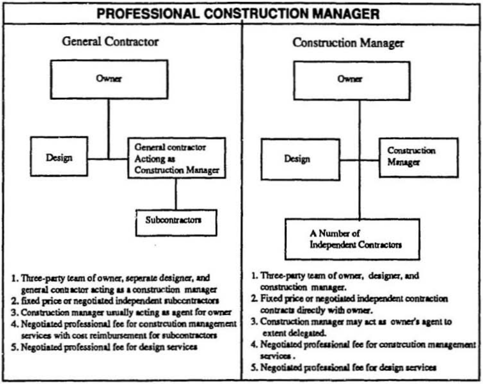


Fig 2-4 Professional Construction Management

(Donald S. Barrie ,1992)

Obviously, construction projects are increasing in complexity. Fifty years ago, a person conceived his project, designed it, and built it himself. We have progressed through the evolutionary stage of master builders to the point that we now have an industry of specialists. A given project is dependent upon numerous parties, including owners, designers, financiers, consultants, accountants, attorneys, constructors and government agencies(see Fig.2-5). It is not surprising that coordination of all the participants is a challenge to the most competent manager.

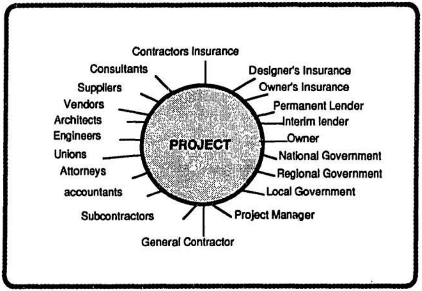


Fig 2-5 Project Participant

(Richard L. Tucker, 1986)

CHAPTER 3. PRODUCTIVITY MEASUREMENT

3.1 Introduction

Due to the fact that misconceptions concerning productivity abound, it is necessary to restate the importance of the concept. Productivity growth is directly linked with increasing real wealth of a nation. Thus, if a general increase in pay is awarded, which is not accompanied by a commensurate increase in productivity, the result will merely be a corresponding adjustment in prices of those goods and services(i.e., inflation). It is not easy to rigorously prove the relationship, in a particular industry, or in the economy as a whole, but the concept accords with common sense, and few would thus dispute that increased output within a particular industry will benefit at least the people connected with that industry.

3.2 The Need For Measuring Design And Construction Productivity

The main input resources in design and construction are labor (including white collar and blue collar), materials and equipment. The cost of these resources form the direct cost of every project. However, material cost unlike that of labor and plant are usually outside the control of the contractor. Moreover, labor and plant costs are unstable and vary within the limits of their control. Labor, for example, is the only input resource whose cost can be completely controlled on site. The greater the control the lower the cost. Control can achieve its aim only when it is within its limits. These limits can be known when the maximum or minimum utilization level and plant are known through productivity measurements.

In recent years, design and construction jobs have become very competitive. Clients want the best service at the minimum cost. Contractors who are able to put in the lowest bid, usually win the job. To be able to bid low, the estimater must know the level of efficiency of such cost sensitive resources like whether the available equipment can complete the job within this period. These can be known by knowing their performance level thorough productivity measurements on previous jobs.

Labor is paid according to the contribution to productivity. This means that every worker must be paid fairly to reciprocate a fair day's work. The meaning of a fair day's work is relative as far as the worker or management is concerned. This controversy can only be resolved by a pre-determined standard satisfactory to both management and labor through known facts provided by measuring the productivity of labor. Management needs productivity levels as a basis of labor cost control.

To motivate workers, management institutes incentive schemes. Management uses the results of productivity measurements as a basis for the payment of wage incentive to direct labor.

Modern construction is very complex, there are times on the site when certain activities will be going on with which the contractor has no previous experience. Meanwhile the value of the products refer to the whole production process, not only the last or final section. So design, transportation, procurement and management etc. should be included. Hence the indirect cost and direct cost should be calculated at the same time. It is, therefore, very important to measure the productivity of labor and plant involved in such an activity both as a cost control measure and as a historical record.

A foreman, or superintendent on site, or design office staff, may notice an operation that does not progress at an acceptable rate, this can best be investigated by productivity analysis.

3.3. Three Major Difficulties In Measuring Productivity

Sometimes, for measurement purposes, productivity is loosely defined in terms of the output of goods or services for a given unit amount of resource input capital, labor, knowledge, and materials . There are three major difficulties which seriously limit the usefulness of such measurements.

First, a single productivity measurement is not very useful by itself, and can be used only for comparisons with the past or with other producers, i.e. , measurements are indicators of relative efficiency (National Research Council 1979). A company recording a productivity measurement comparable with the rest of the industry only learns that it is as efficient (or inefficient) as everyone else. In order to obtain an efficiency measurement in absolute terms it is necessary to have a theoretical maximum with which to compare. This is not easy to come by in the context of the design office. One would hesitate to hazard a guess at the absolute efficiency levels prevailing in the average design office, but figures available suggest that on the construction sites there is still a long way to go. Tucker(1986) quotes figures from a project indicating that only 20% of man-hours were used effectively in putting the project together.

The second difficulty with productivity measurements is that it is difficult to measure what it is really desired to know. In particular, it is difficult to measure the quality of the finished design, although some useful progress has recently been made in this area(Construction Industry Institute 1986). Some of the ideas in this publication will be mentioned later, but it is worth noting at this point that productivity(or effectiveness) should be defined in terms of the output of finished goods and services; in this case complete, constructed and operating designs.

The third difficulty is, there is no general standard for measuring "Brain Work". For instance, the two designers A and B, can design a hotel in totally different ways. Maybe designer A spends ten days for that work, but designer B spends thirty days for the same hotel. It is hard to say whether A's efficiency is higher than B's, because B's design maybe better than A's (for instance, save more money, better satisfy owner etc.). That is why just a few productivity experts research white collar productivity. With the help of fuzzy logic, we may be able to solve some of the "soft" productivity problems.

3.4 Different Measurements Of Productivity

Different measures of productivity serve different purposes. It is important to choose a measure that is appropriate to the purpose. Work-study models serve different goals than productivity models. Substantive discussions require the knowledge of the definition being used.

There are a number of measures of productivity that have application in economics, construction and design. In economics, where the objective is to develop measures for use in policy planning, total factor productivity (TFP) is defined as follows:

ECONOMICS MEASUREMENT:

$$TFP = \frac{\text{Total Output}}{\text{Total Input}} = \frac{\text{Dollars of output}}{\text{Dollars of input}} \quad \text{(Equation 3-1)}$$

$$TFP = \frac{\text{Total Output}}{\text{Labour + Materials + Equipment + Energy + Capital}} \quad \text{(Equation 3-2)}$$

In this thesis , if economic productivity is mentioned, all results are calculated using Equation 3-1 or Equation 3-2.

CONSTRUCTION MEASUREMENT:

In construction we can use this equation to calculate the general productivity:

$$\textbf{Productivity} = \frac{\text{Output (Dollars)}}{\text{Design + Inspection + Construction + Right-of-way (Dollars)}} \qquad \text{(Equation 3-3)}$$

meanwhile , it is usual to measure productivity with reference to project or task performance. Commonly productivity is defined as output per labor cost or output per labor hour. Alternatively the inverse can be used , so that labor productivity can be defined as :

$$\textbf{Labour Productivity} = \frac{\text{Output}}{\text{Labour cost or work-hours}} \qquad \text{(Equation 3-4)}$$

Design Productivity

The question of productivity in the design office is more complex. Current confusion about design productivity appears to stem from at least two problems:

(1) Nonstandard terminology

(2) To use numerical values to calculate or measure the thinking and idea generation processes of engineers and architects is not easy .

Therefore, how to define the design productivity is also a difficult problem, because it includes not only product (drawings), but also services. In most design firms, the manager usually uses building area divided by design work hours to define design productivity.

$$\textbf{Design Productivity} = \frac{\text{Building Area of Design (Square feet)}}{\text{Design Time (Man-hour)}} \qquad \text{(Equation 3-5a)}$$

Maybe a more accurate definition that can be used by governmental agencies for specific program planning and by the private sector for conceptual estimates on individual projects is:

$$\textbf{Design Productivity} = \frac{\text{DF (dollars)}}{\text{(DS + EC + MC + CS + PC) (dollars)}} \qquad \textit{(Equation 3-5b)}$$

here

DF : designing fee (design income)

DS : designer's salary

EC: equipment cost

MC: materials cost

CS: construction service

PC: prime planning cost

3.5 Work Study Models

A work study method is sometimes called a time-motion study. The study is done in two phases. The preferred method of doing the work is first determined (the motion study) and then a time study is done to determine the standard time to perform the task. Common data collection techniques used are time lapse photography, video photography, stopwatch timing and work sampling. Results are commonly presented using gang and crew balance charts, process charts and material flowcharts.

Work sampling is a technique in which a large number of observations are made over a period of time of a construction activity . The crafts people, machines and processes are studied and the percentage of time spent in a number of work states is noted.

The selection of classifications for work requires great care. In construction four "work states" are commonly used and are described below:

Direct Work: This classification of work deals with activities that directly contribute to construction of the project. Examples include craftsmen using tools, a welder welding a worker operating a concrete vibrator etc.

Indirect Work: This classification of work is necessary work in support of, but not an integral part of, direct work. Examples include a craftsman cleaning up, an employee transporting material, workers studying drawings or a craftsman giving instruction to his helpers.

Idle: Idle classification covers activity, or lack thereof, that is unrelated to the project and unexplained. Examples include an employee standing idle while a second one cleans up, a craftsman walking empty handed, employees chatting while getting a glass of water.

Delay: this classification refers to inactivity that is related to unavailability of tools or queuing. Examples include craftsmen waiting in line at the tool shed, employees waiting for materials to be picked up by a crane or employees waiting for direction.

Scarfuto (1985) presents an example of construction work sampling and categorizes time spent as direct work, indirect work, idle time and delay time. Louis and Borcherding(1986) studied the correlation between the results of work sampling measurements and actual productivity. Results showed a close relationship between the two. In addition, the usefulness of work sampling information as applicator in the productivity projection model was demonstrated. Thomas (1991) offered an opposing opinion. The hypothesis that direct work percentages from work sampling studies can be used to predict labor productivity was earned. Data and observations of the investigation was that direct work cannot be used to predict labor productivity.

3.6 Statistical Measurement :

To improve productivity , the impact of each of the variables mentioned by Koehn(1986) on labor productivity can be assessed using statistical methods, and specific attention can be then given to those particular parameters that adversely impact productivity.

Many statistical methods are available that measure the impact of one variable (the dependent variable) on another variable (the independent variable). In addition to being able to predict the value of the dependent variable based on information about an independent variable, a measure of strength of the relationship between these variables can also be determined. One measure of the strength of the relationship between two variables x and y is called *the coefficient of linear correlation (r)* , or simply the correlation coefficient. Given n pair of observations(x_i, , y_i), the sample correlation coefficient r can be computed as :

$$r = \frac{S_{xy}}{\sqrt{S_{xx}S_{yy}}} \qquad \text{(Equation 3-6)}$$

where:

$$S_{xy} = \sum xy - \frac{(\sum x)(\sum y)}{n}$$

$$S_{xx} = \sum x^2 - \frac{(\sum x)^2}{n} \quad , \quad \text{and}$$

$$S_{yy} = \sum y^2 - \frac{(\sum y)^2}{n} \quad , \quad \text{so}$$

In order to find the proportion (r^2) of the total variables of the y-values that are accounted for by the independent variable x , the following equation can be used:

$$r^2 = \frac{S_{xy}^2}{S_{xx}S_{yy}} \qquad \text{(Equation 3-7)}$$

Similarly, $1 - r^2$ represents that proportion of the total variability of the y -values that are not accounted for by the x variable. The equations described above can be used if, and only if, there is a linear relationship between x and y. Other models become necessary when the relationship between x and y is not linear; that is, y increases or decreases with x but not in a linear fashion. The approach used in this study was the rank correlation coefficient, which measures the monatomic relationship between y and x; that is, y increases or decreases with x even when the relation between y and x is nonlinear.

3.7 Using Fuzzy Relational Data-Base To Measure The Problems Of Design and Construction.

(1).Concept of Fuzzy Set:

Fuzziness represents situations where membership in sets cannot be defined on a yes/no basis because the boundaries of sets are vague(Zadeh 1965). The central concept of fuzzy-set theory is the membership function, which numerically represents the degree to which an element belongs to a set. In a classical set, a sharp or unambiguous distinction exists between the members and non members of the set. In other words, the value of the membership function of each element in the classical set is either 1 for members (those that certainly belong into the set) or 0 for numbers (those that certainly do not). However, many sets, such as the sets of complex system, nice houses, beautiful place, and numbers much greater than 1.0, do not exhibit this characteristic, that is , their boundaries are fuzzy.

The analysis of the basic criteria for the design/construction problem is estimated as fuzzy values to characterize their uncertainty. The fuzzy values are numbers that belong to a given set (interval) with a degree of membership. To evaluate the various design/construction problems under uncertainty, let $Z_i(X)$ be a fuzzy value for the i th basic criterion, and let its membership function $m[Z_i(x)]$ be a trapezoid (Fig 3-1), where x is one element (problem name) of the discrete set of design/construction problems. If the trapezoid is reduced to a vertical line, it represents a so-called crisp(nonfuzzy) number. A level-cut concept (Dong and Shah 1987) can be used to define the interval of each basic criterion at various degrees of membership. The membership degree for an uncertain value can be determined using "expert judgment" based on experience and observation variability . As shown in Fig 3-2, $Z_{i,h}(x)$ is the interval value of the ith basic criterion at the membership degree h(i.e., $a < Z_{i,h}(x) < b$).

1. If $BESZ_i > WORZ_i$, then

$$S_{i,h}(x) = \left[\begin{array}{ll} 1, & Z_{i,h}(X) \geq BESZ_i \\ [Z_{i,h}(x) - WORZ_i]/(BESZ_i - WORZ_i), & BESZ_i < Z_{i,h}(X) < WORZ_i \\ 0, & Z_{i,h}(x) \leq WORZ_i \end{array} \right]$$

(Equation 3-8)

2). If $BESZ_i < WORZ_i$, then

$$S_{i,h}(x) = \left[\begin{array}{ll} 1, & Z_{i,h}(X) \leq BESZ_i \\ [Z_{i,h}(x) - WORZ_i]/(BESZ_i - WORZ_i), & BESZ_i < Z_{i,h}(X) < WORZ_i \\ 0, & Z_{i,h}(x) \geq WORZ_i \end{array} \right]$$

(Equation 3-9)

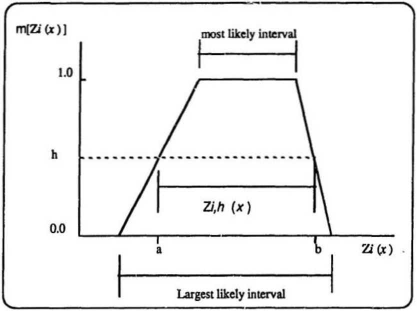


Fig 3-1 Fuzzy Estimate of *ith* Basic Criterion

Since the units of the basic criteria are different (such as technical factors not being expressed in units at all while the cost is in dollars), thus making it difficult to compare them directly, the actual value of each basic criterion [*Zi,h(x)*] should be transformed into an index. Using the best value (BESZ*i*) of *Zi* and the worst value (WORZ*i*) of *Zi* for the *i* th basic criterion, the actual value *Zi,h(x)* can be transformed into an index value *Si,h (x)* as indicated by (Fig 3-2)

To assign the best and worst values(i.e. $BESZ_i$ and $WORZ_i$) of the *i* th basic criterion, one of two options can be used. The first is to assign the best and worst values of the *i* th basic criterion according to the overall best and worst values of the *i* th basic criterion among the design/construction problems considered. The second option is to assign the best and worst values of the *i* th basic criterion according to the opinion of an expert. Since the actual value $Z_{i,h}(x)$ is an interval with lower bound a and upper bound b (Fig 3-1), the index value $S_{i,h}(x)$ resulting from $Z_{i,h}(x)$ is also an interval (Fig 3-2).

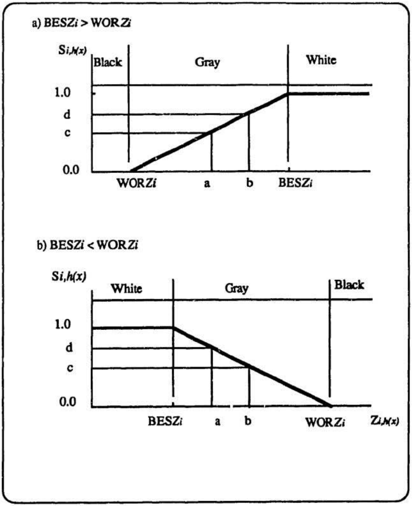


Fig 3-2 Transferring Actual Value $Z_{i,h}(x)$ into index Value $S_{i,h}(x)$

In design and construction productivity measurement, many problems are "fuzzy". For instance, it is very hard to measure one engineer's idea using "input" or "output". To measure design quality is also a complex procedure. What is the meaning of "Excellent design?" "Very good construction?". From "poor" (0) to "excellent" (1), we have to go through a "gray" area. (from 0 to 1).

(2). Fuzzy Relation Data-Base

In this thesis the author wants to use the Fuzzy Relation Data-Base system to analyze the relationship between design and construction. Because the Fuzzy Relation Data-Base(FRDB) (Candel, 1986) model was designed to satisfy the requirements for sound formal foundations, real-world information models, individualization, and user's convenience. The Relational Data-Base structure combined with the theory of fuzzy sets provide a solid theoretical foundation. The query language permits "natural-language-like" expressions that are easily understood by users, and can be further developed to incorporate fuzzy inferences or production rules. An experimental FRDB system was developed to test the feasibility of an imprecise information system. The FRDB has been used as a useful tool to evaluate the complexity of engineering problems where there are conflicting objectives, the objectives have varying degrees of importance, and values of input variables are uncertain(A. Kandel 1986, Lee et. al. 1991, Z.X. He et. al. 1992,). This is a multilevel, multiobjective method using fuzzy sets to represent the uncertainty in input variables. The specific objectives of this study are two fields. The first objective is to develop an evaluation support system based on a FRDB method(Table 3-1 and Table 3-2), the second is to apply the evaluation support system to forecast the deviation of design and construction.

In Chapter 6, the author will introduce the use of the Single Factor Evaluation method of FRDB system to evaluate the complexity of design and construction projects.

Chapter 4. DESIGN PRODUCTIVITY

4.1. Introduction

The design productivity problem is closely linked to the design quality problem. A lot of research shows that high quality design can tangibly reduce the cost of construction. There are two ways to discuss the design quality problems, that are the economical and technical way. In this chapter, the author will, from an economical view point, discuss the influence of design on productivity in construction; the compression of design cost and construction cost; optimum design and design decisions.

The term "design" is defined as the creation of plans and specifications that result in the allocation of resources, to accomplish a project(Dickerson and Robertshaw 1975.). Design consists of three sub processes: (1) defining the problem, or the "conceptual phase"; (2) generating and evaluating alternatives, or the "preliminary design phase"; and (3) reducing the best solution to a description for construction, or the "detailed design phase." In some engineering disciplines, design consists of a test and revision stage; this stage is not generally applicable in construction. On the other hand, construction design must include the revisions and interpretations that occur during construction. Construction design includes planning, cost, schedule, and quality functions that lead to the specification of construction conditions. In some countries, detailed design include construction drawing, even include materials specification, for instance, steel bar specification, wood specification, or materials list and installation specification.

4.2. Design Process

The progress of a project from the initial idea to engineering reality is depicted by a process such as that shown in Fig.4 -1(McGeorge, 1988). This diagram gives a picture which is too rough and simple. There are other aspects which could be added to Fig.4-1, such as commissioning , operating, maintaining, and decommissioning. These processes are also very important. However, the fact is that different design offices have different customers, and different projects have different characteristics. All of these have been omitted in this as not essential to the argument. It is essential that these factors be taken into account when assessing the life cost of a project. From this figure, we can see that not only design is a product process but also a service process, from project investigation until the construction has been completed. Service is a continuous process.

Furthermore, designs are not produced just by draftsmen (or by engineers) , but by a system of resources working as a team. To return to the construction site analogy, it is no good speeding up the rate of concrete placement if that only means that the operator has to wait for the formwork crew. In a similar way delays and disruptions are the biggest impediment to productivity(and morale) on the site. Hence design office output is affected by failures of the system to function properly. Failure of the system usually manifests itself in shortage of a key resource; material, labor, equipment, or information (especially concerning decisions on critical issues). The most important of these, in the design office context, is information. The engine which drives the design system is the brain power of its members, and the fuel which powers it is information. The design office is the quintessential information processing system. Information drawn from a host of sources —— the marketplace , design codes, technical, material, the client's terms of reference, the knowledge and experience of the designers--- is processed into something which is (hopefully) elegant, useful, and economical.

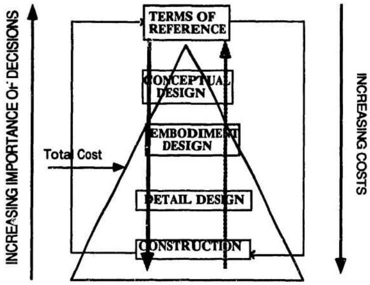


Fig 4-1 **Project Design Process**

(John F.McGeorge, 1988)

It was stated earlier that productivity must be defined in terms of the output of finished goods and services, i.e. , activity does not equal productivity. In order to be productive, an activity must contribute towards the attainment of the desired goal. It is necessary that the draftsman is not just active, but productive, and to achieve this requires that attention be given to the nature of the design process.

4. 3. Design Input and Construction Cost

The second feature of the process is that the cost of completing each stage increases rapidly, in more or less exponential fashion, as indicated by the cost pyramid. The cost of design is generally considered to be roughly between 2% and 10% of the total costs (Institution of Civil Engineers 1985). The implications of this are interesting. Since design costs represent only a small proportion of total costs, it becomes worthwhile to increase the design effort significantly in order to achieve comparatively small reductions in construction cost. A simple example (McGeorge, 1988), using a design cost of 5% is shown in Table 4-1.

Table 4-1

Effect of Extra Design Input

Item	Costs($ thousands) Original design	Costs($ thousands) Revised design
Design cost	50	50+(50x50%)=75
Construction cost	950	950 - (950x10%)=855
Total cost	1000	830
Overall Saving		70(7%)

In this case it has been assumed that a 50% increase in design input yields a 10% saving in construction cost. The net result is a 7% reduction in total cost, or a saving almost 3 times the cost of the extra design work. It should be questioned, of course, whether such figures are realistic, and the evidence available indicates that they are. In fact, rather than overstate, research carried out on constructability, For example, indicates that constructability and value engineering reviews typically yield construction cost savings of 10 to 20 times the cost of the extra design input(Business Round Table 1982). Even these figures understate the true potential for improvements, as constructability exercises, by definition, aim at reducing only construction costs, and the picture is improved by including operating and maintenance costs, which frequently exceed construction cost. To take one example, recently compiled figures on hospitals indicate that operating costs exceed the capital cost of building a hospital within only 2 to 3 years of operation (National Building Research Institute 1985).

4.4 Optimum Design

(1). The balance between design input and construction cost

Naturally, improvements cannot continue to be made indefinitely. At some point an increase in design input will yield an insignificant saving on construction, and total cost will be higher. Thus, plotting design effort against total cost yields a curve like the one shown in Fig 4-2. A rational policy then would be to aim for the optimum design effort *'o'*, but the implications of the foregoing discussion are that most engineering projects fall well to the left, at some point *'a'*. The success of constructability programs is a result of recognizing and acting upon this simple and obvious fact.

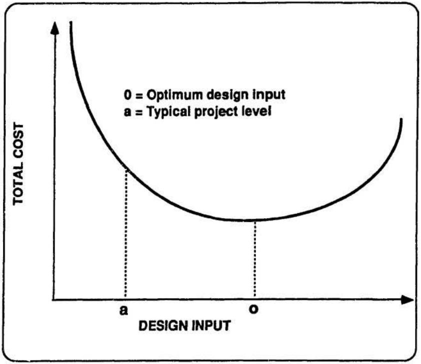


Fig 4- 2 Effect of Design Effort on Project Cost

(2). The Balance between Multifactor cost

Note, usually the "optimum " or "cheapest" means from a total cost viewpoint, and does not refer to any individual cost. We have to understand that the most economic design is not necessarily the cheapest; it is the one which gives the best value for money. In the productive sector of the economy, the objective is to produce goods and services, not for their own sake, but in order to make a profit. The final criterion for the entrepreneur is the difference between revenue and expenditure and the relationship of this difference to the capital employed. The building is one of these expenses.

For instance, the cost of a building to an owner can be visualized in three parts. The first part is the cost of construction, this is basic because the owner's needs establish what functions and size a building should have. The resulting design sets construction costs. All other costs are related to, or are a function of, construction costs. The second part of the cost of a building includes all those expenses that an owner must incur, other than construction, before a building can be occupied. The third part of the cost of a building takes in all the expenses incurred by the owner during its useful life. These latter are life-cycle costs. The cost of operations and maintenance depends in large part on the initial cost and on the quality of the architectural and engineering building systems. Low initial building costs achieved by the sacrifice of quality can result in high life-cycle costs.

Figure 4-3 illustrates these three parts of the cost of a building. The first column shows that, on the average, architectural building systems account for about 39 percent of the construction costs, structural engineering systems 25 percent, and mechanical engineering systems 36% percent. The second column illustrated other costs before occupancy. Land is a large variable and can be significant in downtown urban locations. (Sometimes the land cost may account for up to 50-100 percent or more of the building.) The third column shows that total building costs over many years dwarf the initial cost of construction.

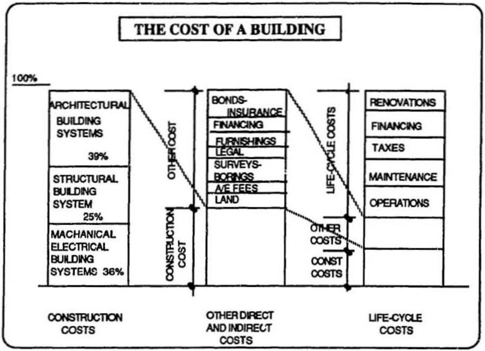


Fig 4-3 A Building Cost Analysis

We can use this to express the relationship of the various cost for optimization purposes.

Minimum cost = Construction Cost + Other direct and indirect Cost + Life-Cycle Cost

s.t. $\left[\begin{array}{l} \text{Construction Cost} > 0 \\ \text{Other direct and indirect cost} > 0 \\ \text{Life-Cycle Cost} > 0 \end{array}\right]$

Figure 4-3 gives only a broad picture of the owner's building costs. Some owners have all the expertise needed to determine their costs; they establish the number of dollars available for construction, negotiate a fee with their architect and engineer , pin down all other costs, and determine their entire fiscal future. Other owners depend on architects and their engineer and cost managers for a good deal of this information, and these design professionals must speak the language of dollars as spoken by the building owner.

Since the building interacts with the other costs of production activity or process carried on in the building, it is not sufficient simply to minimize the costs of the building itself. The objective is to minimize the costs of the process as a whole; the costs - in use being interpreted in a wider sense to include all the expenses of operating within the building as well as the costs of operating the building itself. The value of the building is its contribution to the activities carried out in it. Its cost is simply part of the production cost. In contrast, in the consumption sector of the economy , the building is the final product which has a cost on the one hand and a value on the other. The value of a building is inevitably subjective and hence difficult to assess. However, since the determination of the optimum design is a comparative exercise, it is only necessary to compare the value features which differ and this is usually easier. The difference in value between two buildings can be compared against the difference in their costs-in- use. Thus , the final choice between alternative designs can be made in terms of the differences between the ratios of value and cost.

A further implication, and one well recognized by most people who do constructability assessments, is that the largest gains can be made early in the process, or high up on the scale of "Importance of decisions"(Construction Industry Institute 1986). However , to get the figures on the cost of conceptual design as a percentage of total design cost is not an easy thing since its complexity and uncertainty, but a relationship similar to that between design and construction may be reasonably inferred. Anyway, at least in the structural design process, concept design becomes more and more important. For instance, seismic structure design, only adds two percent structure cost for a building that can effectively resist an earthquake of 7 - 8 on the Richter-Scale. In achieving this slight cost increase, the concept plays a role. It is not just a matter of adding some rebars to the concrete , but of focusing on how best to arrange the columns and shear-walls in the building. One correct decision can save thousands of dollars.

4.5 Design Decisions

Early decisions are basic decisions that establish design and cost. Controlling early decisions produces maximum benefit and can effectively reduce the construction deviations. A wrong decision about community reaction to a proposed building, made during the impact-analysis phases could result in the project never being built for lack of public approval. It is important to make the right decision in selecting a schematic design concept from among a group of alternatives. The building system decision is the first in a chain of decisions, all of which must be made within the limiting parameters of the concept. The decisions follow the building system selection. Design and cost flexibility is limited to subsystem and component selection within the boundaries of that system.

Figure 4-4 (FIFA 1980) illustrates the cost of wrong and right decisions and shows that maximum penalties and benefits accrue from the early stages of a project and that after the design phase there is little that can be done to change its cost. It also points out how detrimental is to try to avoid assessing the cost impact of design decisions.

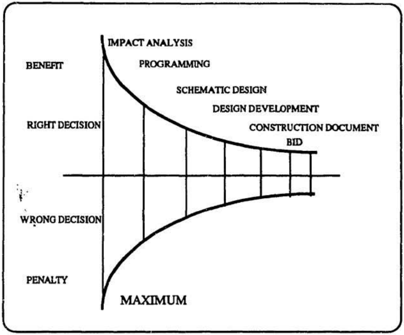


Fig 4-4. Design Decision and Construction Cost

(Herbert Swinburne, FAIA ,1980)

CHAPTER 5. CAUSES OF LOW PRODUCTIVITY IN CONSTRUCTION

5.1 Introduction

The research presented in this chapter was conducted to identify the technical causes and magnitude of quality problems in design and construction and to determine the costs associated with the quality problems. This is the second way to discuss design influence on productivity of Construction. The detailed analysis of the several deviations and its distribution leads to the idea of design quality . A good design will be effective (i.e. , serve the purpose for which it was intended with best possible economy and safety.).

The author believes the best definition of quality is the one proposed by ASCE in its Quality in the constructed Project (1990). That is "Quality in the constructed project is achieved if the completed project conforms to the stated requirements of the principal participants(owner, design professional, constructor) while conforming to applicable codes, safety requirements, and regulations". Simply stated, this definition says that quality is meeting the stated and agree-upon requirements of the project.

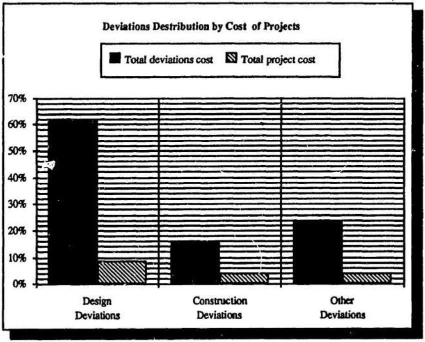
Thus design productivity in its broadest sense (considering whole life costs) is a quality problem. From the investigation by the author, it is known that design deficiencies are a major cause of contract disputes and changes during construction. The analyses of the data indicate that deviations on the projects accounted for an average of 16.5% of the total project costs. Furthermore, design deviations average 68.1% of the total number of deviations, 61.1% of the total deviation cost and 8.6% of the total project cost. Construction deviations average 16% of the total number of deviations , 15.3% of the total deviation costs, and 4% of the total project cost. See Table 5-1 and Fig 5-1.

Table 5-1

Deviation Distribution

Item	Total deviations cost (%)	Total project cost (%)	Total Deviation number(%)
Design Deviations	61.1%	8.6%	68.1%
Construction Deviations	15.3%	4%	16%
Other Deviations	23.6%	3.9%	15.9%
Sum	100%	16.5%	100%

Fig 5-1 Deviations Distribution by Cost of Project



5.2. Deviation Data Collected

What is Deviation?

Deviation: In the construction industry , rather than failure or defect (which are commonly used in manufacturing industries), indicates that a product or result that does not fully conform to all specification requirements does not necessarily constitute an outright failure (Davis et al. 1989)

Deviation includes changes to the requirements that result in rework, as well as products or results that do not conform to all specification requirements, but do not require rework.

Wherever possible , data were collected directly from field change orders, requests for information, or design change orders that contained complete information concerning

(1). A description of the change;

(2). Why the change was required;

(3). Who initiated the change;

(4). The cost of the change.

Some information is adapted from ten projects which the author designed in China, some adapted from the projects which the author investigated in Canada. When information was not available , other sources, including cost accounting tabulations and computerized project summaries, were investigated. When complete information was not available from the alternate data sources, additional information was obtained through interviews with project representatives in order to gain sufficient understanding for analysis of the data.

The deviation data that were collected and analyzed were limited to the structural design and construction (including fabrication) phases of the projects studied. The deviation data collected included only the direct costs associated with rework (including repair and replacement) and therefore do not constitute the total costs associated with the deviations. These direct costs of correction deviations are only the "tip of the iceberg". Impact costs, such as the effects of the rework on the project schedule or on other project activities , were not generally available and are not included in the deviation costs presented herein. In addition , no data were available on the costs associated with quality management activities. The Table 5-2 is the Description of Projects Studies.(in these cases the inflation was not be considered)

TABLE 5-2. Descriptions of Projects Studied

PROJECT	TYPE OF STRUCTURE	TYPE OF USE	BUILDING AREA (METER SQUARE)
A	Concrete Frame	Public	60,000
B	Concrete Frame	Public	45,000
C	Concrete Frame	Industry	78,000
D	Steel Structure	Public	45,000
E	Steel Structure	Public	112,000
F	Steel Structure	Industry	18,000
G	Masonry Structure	Public	9,000
H	Masonry Structure	Residential	30,000
I	Masonry Structure	Residential	23,000
J	Flat-Plate	Public	12,000

5.3 Classifying Deviation Data

The deviation data collected on the ten projects were classified to allow a more descriptive analysis of the causes of the deviations and their associated costs. The deviation data were divided into five major areas---design, construction, fabrication, transportation, and operation. Each of these areas were further subdivided by type of deviation.

For the projects studied, a large percentage of the deviations were due to design changes (over 50% of the total number of deviations). To better define the costs associated with design changes , the deviation category for design changes was expanded to seven design-change categories.

5.4 Design Deviations

Design deviations are related to the design of the project. Design errors (DE) are the result of mistakes or errors made in the project design. Design omissions(DO) result when a necessary item or component is omitted from the design. Design changes occur when changes are made in the project design or requirements , and are further classified as follows:

(1) Design Change /Improvement (DCI)

DCI includes only design revisions, modifications, and improvements initiated through the design process. For instance , the result of design reviews, model reviews, and technological advances. Changes initiated for any other reason are classified under one of the other design change designations.

(2) Design Change/Construction (DCC)

DCC is changes in design made at the request of the field or construction personnel. An example of this is addition of concrete pads to permit proper installation of equipment.

(3) Design Change/Field (DCF)

DCF is design changes due to field conditions in retrofit and upgrade projects. An example of this is when the existing structure, equipment, or pipe location differs from the details given on available drawings, and the deviation could not have been foreseen by the designer.

(4). Design change/Owner (DCO)

DCO is changes in the project design initiated by the owner. Examples of this are a change in project scope or things like additional electrical outlets in an office.

(5).Design Change/Process (DCP)

DCP is design changes in the process portion of the facility initiated by an owner's representative or consultant familiar with the expected operations and processes to be fulfilled by the activity. An example of this is the addition of valves, pumps, electrical equipment, or instrumentation that affect the operation of the completed facility.

(6).Design Change/ Fabrication (DCR)

DCR is changes in design initiated or requested by the fabricator or supplier. An example of this is a fabricator request for a change in vessel dimensions to provide uniformity between parts.

(7).Design Change/Unknown (DCU)

DCU is design changes for which the description does not yield enough information regarding the reason or source of change, and discussion with the project representative affords no insight . An example of this is a change with a description such as "structural steel design change ." While this change may have been an improvement in design or the result of a model review, it may also have been a redesign due to an error.

5.5 Construction Deviations

Construction deviations are related to the construction phase of the project and consist of those activities and tasks that take place at the project site. A construction change (CC) is defined as a change in the method of construction, such as placing concrete by pump rather than by bucket. Construction changes are usually made to change the constructability of the project. Deviations classified as construction errors (CE) are the result of erroneous construction methods or procedures. Construction omissions (CO) are those deviations that occur due to the omission of some construction activity or task.

5.6 Administration and Owners Deviation

The government may change regulations or they may pursue some new procedures. For instance, they do not permit use of some materials or publishes new traffic policies. Often designers are asked to change their design. Sometimes the owners change their mind. In commercial projects we usually meet these situations. For example, the manager of a supermarket finds that he needs extra space for some new product . He asks the architects to change the design . We identify it as "Administration and Owners Deviation(AOD)"

5.7 Fabrication Deviation

Fabrication deviations are related to shop fabrication change errors. Omissions that occur during field fabrication are included in the construction deviation categories. Fabrication change, errors, and omissions are those deviations that occur, or are the result of, work performed by a vendor, fabricator, or supplier. A change made in or during fabrication is classified as a fabrication change (FC) . Fabricated parts that are not in accordance with the specifications are noted as fabrication errors(FE), while parts or pieces that are included in the specifications but are not supplied are denoted as fabrication omissions(FO).

5.8 Transportation Deviations

Transportation deviations are related to the transport of equipment, materials, or supplies. A transportation change (TC) indicates a change in the method of shipment , e.g., shipping by air to expedite delivery rather than shipping by truck . Transportation errors(TE) denote errors made in transporting a product, e.g., shipping an article in separate pieces when the specification requires the shipment of an assembled product.

Transportation omissions(TO) occur when a required part or item is not included in the appropriate shipment.

5.9 Operation Deviation

A differentiation was made between changes, errors and omissions made to the operation or process portion of the facility and those changes made to improve operability. An operations change might be the use of two pumps instead of one, or the addition of check valves in a required line; while an operability improvement might be relocating valve handles to improve operator access. Changes in operability are denoted with the deviation code(OC) , while changes made in the operation or process portion of the facility are included in a specific design-change category. There is no need for error or omission categories for operability since errors and omissions in operability are the result of an error or omission made in design , fabrication , or construction.

5.10 Analysis of Data

The data were analyzed in terms of the number of and costs of deviations. Since the size of each of the projects (in total cost) varies, comparisons of the number of deviations and deviation costs were all performed on a percentage basis to allow comparisons among the projects to be made. The analyses consisted of the number of deviations, deviation costs as a percentage of total project deviation costs, and deviation costs as a percentage of total project cost.

5.11 Design Deviation Is The Major Part Of Total Deviations

Table 5-3 and Fig 5-2 presents the number of deviations in the design, construction, fabrication, transportation, and operation areas as a percentage of the total number of deviations on the project. The greatest number of deviations occurred in the design and construction areas . Design deviations accounted for 47.7%-90.7% of the total number of deviations on the projects , while construction deviations ranged from 2.3-20.3% of the total number of deviations. It shows that the major part of deviation is design deviation.

Table 5-3 Number Of Deviations As Percentage Of Total Number Of Deviations Of Each Project

AREA	PROJECT										AVERAGE
	A	B	C	D	E	F	G	H	I	J	
DESIGN	77.2	90.7	79.1	55	75.1	69	61.8	51.9	47.7	65.3	67.3
CONSTRUCTION	4.5	2.3	7.5	21.3	12.5	7.5	15.3	20.3	18.4	11.8	12.1
FABRICATION	13.4	5.7	12.3	1.2	1.4	2.3	3.5	11.1	3.1	6.5	6.2
TRANSPORTATION	2.5	1.2	0.8	4.3	10.7	9.3	8.9	0.9	15.3	5.9	5.9
OPERATION	2.4	0.1	0.3	18.2	0.3	11.9	10.5	15.8	15.5	7.9	8.4

Fig 5-2

Number of Deviations as Percentage of Total Number

of Deviations

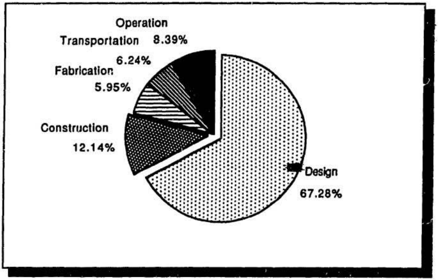


Table 5-4 shows the percentage of the total number of deviations for design changes, errors, and omissions for each project. Design changes in design were not recorded unless they were the result of an error or omission. Fig 5-3 shows the design deviations as percentage of total number of different deviations. We can see that the major reasons for design deviations are Owner change (18%), Design error (19%), Fabrication (10.09%), and Field change and construction (10%).

TABLE 5-4

NUMBER OF DESIGN DEVIATIONS AS PERCENTAGE OF TOTAL NUMBER OF DEVIATIONS OF EACH PROJECT

DEVIATION CATEGORY	PROJECT										AVERAGE
	A	B	C	D	E	F	G	H	I	J	
DESIGN CHANGE/ IMPROVEMENT	7.2	6.9	3.5	1.1	2.3	3.4	8.3	12.7	11.2	2.6	5.9
DESIGN CHANGE/ CONSTRUCTION	0.1	2.0	6.7	12.9	13.4	4.5	6.7	2.4	3.2	18.7	7.1
DESIGN CHANGE/ FIELD	5.3	5.3	2.1	7.8	10.7	15.4	5.6	4.6	5.3	12.8	7.5
DESIGN CHANGE/ OWNER	12.0	7.5	15.9	0.0	13.3	23.6	15.5	18.4	14.8	6.7	12.8
DESIGN CHANGE/ PROCESS	10.1	3.9	8.9	1.2	0.5	0.8	4.5	3.8	2.7	2.3	3.9
DESIGN CHANGE/ FABRICATION	21.2	32.1	23.5	1.3	3.4	2.3	1.6	0.8	2.3	12.4	10.1
DESIGN CHANGE/ UNKNOWN	1.7	5.2	1.1	7.9	3.2	7.1	12.6	4.5	3.5	2.8	4.9
DESIGN CHANGE/ TOTAL	57.6	62.9	61.7	32.2	46.8	57.1	54.8	47.2	43	58.3	52.2
DESIGN ERROR	19.1	21.9	15.3	21.5	18.7	7.8	6.4	3.8	4.2	5.1	12.4
DESIGN OMISSION	0.5	5.9	2.1	1.3	9.6	4.1	0.6	0.9	0.5	1.9	2.7
DESIGN TOTAL	77.2	90.7	79.1	55.0	75.1	69.0	61.8	51.9	47.7	65.3	67.3

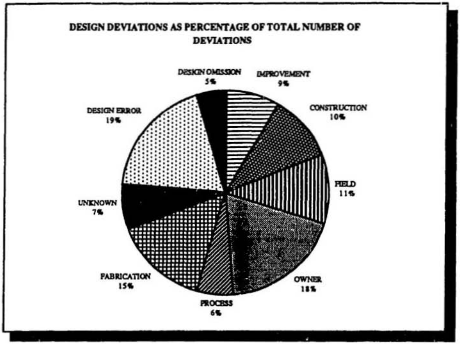


Fig 5-3 Design Deviations As Percentage Of Total Number Of Deviations

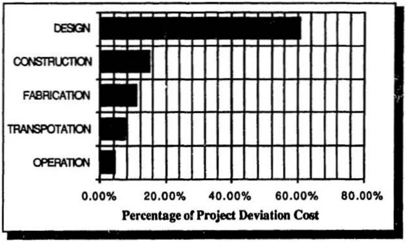
5.12. Cost of deviations

Table 5-5 presents the deviation costs for each area as percentages of the total deviation cost for each project. Fig. 5-4 presents the ten-project averages for the same data. Since design deviations accounted for such a large percentage of the deviations, Fig 5-4 presents a breakdown of the design deviations. Deviation costs for the design-change categories amounted to an average of 61.14% of the total deviation costs.

TABLE 5-5 DEVIATION COSTS AS PERCENTAGE OF TOTAL PROJECT

	DEVIATIONS COSTS										
	PROJECT										
AREA	A	B	C	D	E	F	G	H	I	J	AVERAGE
DESIGN	59.6	61.7	57.8	55.3	63.2	72.1	63.8	63.9	51.4	62.6	61.1
CONSTRUCTION	2.3	3.1	4.5	30.4	15.8	4.7	13.5	23.4	35.9	19.7	15.3
FABRICATION	29.1	30.1	25.5	3.2	2.3	5.7	4.2	3.5	4.5	3.8	11.2
TRANSPORTATION	1.3	2.9	7.7	9.8	12.9	10.4	9.7	8.8	5.3	6.4	7.5
OPERATION	7.7	2.2	4.5	1.3	5.8	7.1	8.8	0.4	2.9	7.5	4.8

FIG 5-4 The Average of Total Project Deviation Costs



5.13 Deviation Distribution

From research it was found that different structural styles have different deviation distributions. For instance, masonry structure design deviation is relatively low(53.9%) but construction deviation high(36%), and concrete structure design deviation is high (82.3%) but construction deviation low(15.7%). See Table 5-6 and Fig 5-5 for detail.

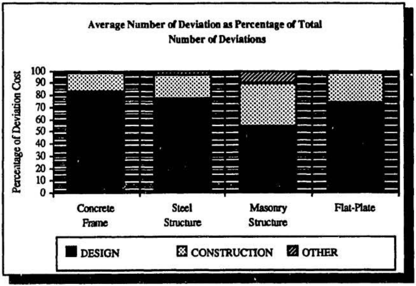
TABLE 5-6

AVERAGE NUMBER OF DEVIATIONS AS PERCENTAGE OF TOTAL NUMBER OF DEVIATIONS OF EACH PROJECT

DEVIATION CATEGORY	TYPE OF STRUCTURE				
	CONCRETE (3 Projects)	STEEL (3 Projects)	MASONRY (3 Projects)	FLAT-PLATE (1 Project)	AVERAGE (10 Projects)
CONSTRUCTION CHANGE	8.5	12.3	20.1	12.9	13.5
CONSTRUCTION ERROR	6.9	6.1	5.8	9.1	7
CONSTRUCTION OMISSION	0.3	1.2	10.1	2.9	3.6
CONSTRUCTION TOTAL	**15.7**	**19.6**	**36**	**24.9**	**24.1**
DESIGN CHANGE/IMPROVEMENT	5.9	2.3	10.7	2.6	5.4
DESIGN CHANGE/CONSTRUCTION	2.9	10.3	4.1	18.7	9
DESIGN CHANGE/FIELD	4.2	11.3	5.2	12.8	8.4
DESIGN CHANGE/OWNER	11.8	12.3	16.2	6.7	11.8
DESIGN CHANGE/PROCESS	7.6	0.8	3.7	2.3	3.6
DESIGN CHANGE/FABRICATION	25.6	2.3	1.6	12.4	10.5
DESIGN CHANGE/UNKNOWN	2.7	6.1	6.9	2.8	4.6
DESIGN ERROR	18.8	16	4.8	8.9	12.1
DESIGN OMISSION	2.8	15	0.7	5.9	6.1
DESIGN TOTAL	**82.3**	**76.4**	**53.9**	**73.1**	**71.4**
OTHER	**2**	**4**	**10.1**	**2**	**4.5**

The average values for the design deviation categories are broken down in Fig 5-6.

Fig 5-6



Using Fig 5-6 and Table 5-7, when we know what kind of structure, the deviation distribution can be forecasted , so in the next chapter we will use these tables to forecast design and construction deviations.

CHAPTER 6. FORECASTING DESIGN AND CONSTRUCTION DEVIATIONS

6.1 Introduction

For years, control of construction quality was considered the responsibility of the trades foreman on the job site. Quality control was mainly the task of inspecting the work and repairing or redoing any work that was considered unacceptable. However, project managers finally recognized that this process was both incomplete and ineffective. In some big design companies, they have extensive management procedures. In small companies, there is very little in the way of formal management procedures. Of course, efforts were needed to prevent incorrect or out-of-specification work. Quality problems were not limited to just the construction site.

The goal of an owner is to have a project that incorporates the latest technology with the capacity to meet project cost and scheduling objectives. This goal has resulted in fast-track construction of these projects. The trade-offs for the compressed schedule have been problems of undefined scope due to last-minute design, design changes, and incomplete designs before construction starts. These design-related problems are often not found until the construction phase of the project with the results being stoppages of work or the need for rework, increased project costs, and schedule extensions. Constructability and value-engineering studies have been undertaken to bring construction expertise into the design phase to eliminate design-related problems. Generally, management has not been able to determine the magnitude of these problems and how effective these studies are.

The best way to control design and construction quality is to establish a data base of problems detected from past projects and to use that information for predicting the number of problems that can be anticipated in the future project. These problems are discovered during the actual construction of the project, but the majority of these problems originate in the design phase. Currently, there is no documentation linking these problems to the design phase where the actual cause of the problem can be determined.

Generally speaking, predictors can be found, two feedback loops can be established to benefit the design from the information discovered during construction. For ongoing projects , a short-term feedback loop uses the data gathered during problems, a long-term feedback loop tracks the results from completed projects to build a data base. Designers could use these data to prevent recurring problems on future projects of similar design.

However, the objectives of maximizing technical performance and minimizing cost and time are in conflict. The evaluation of the technical performence factors, cost and time, are associated with uncertainty. With the help of Fuzzy Logic theory we can solve these problems. (The basic fuzzy theory has been introduced in Chapter 3).

In this thesis, the author uses ten projects (which have been described in Chapter 5) to research how the design deviations influence construction. The ten structures were divided into four groups. They are: concrete frame structure, steel structure, masonry structure, and Flat-plate structure. Because of this, the projects can be analyzed as four different structures.

6.2 Methodology:

The data collected from the real projects which were designed by the author in China, also include some projects which were investigated by the author in Canada. As mentioned earlier, the Canadian projects were not included in the analysis due to lack of some crucial pieces of imformation.The information from China was entered into a data base and analyzed using various statistical techniques and fuzzy logic.

6.3 Limitations found in the projects

(1) In Chapter 5 the author has describted the cost problems in details (see Fig 5-8 and Table 5-8), so in this Chapter cost problems are not considered.

(2) The data doesn't reflect the skill level of different engineers.

(3) Some information is not included. For instance, the equipment , the computerization level etc. Conclusions drawn from the projects are therefore made in general terms and not with the accuracy usually associated with objective data. Finally the author gives four forecasting equations .

6.4 Problem Categories

In this thesis, the author uses the categories method developed by Smith(1983) and Bliudzus & Ashley(1985), Glavan(1991). The categories used in these references were an excellent start for this study; however, no single system totally captured the detail necessary . To study the types of problems that arise in the construction phase of a project, a hierarchy of problem categories must be established. Various accepted categories of problems used in the construction industry vary according to intended uses. After a review of the existing categories and an initial classification of the projects, eight categories were chosen. These categories, along with subcategories, are as follows:

. **Drawings:** Classification when questions to problems arise related to a drawing.

. Interference.

. Discrepancy.

. Omissions.

. Error.

. **Schedule:** Problems that could affect the schedule. Used when delays are encountered because of missing information or drawings. This category is also used with information.

. Information needed.

. Information provided.

. Drawing needed.

.Design : Category used when changes to the original design result in engineering rework or when the memo identifies design deficiencies.

. Error.

. Change.

. Scope: Defines the work to be accomplished and accounts for additional work.

. Procurement: Category used to cover vendor problems, material problems, or requests for field purchase.

. Engineering for field purchase.

. Commodities.

. Field purchases.

. Vendor problems.

. Fabrication.

. Specifications: Category used when there is a question concerning the specification, a request for a material substitution or the correctness of a particular specification.

. Clarification.

. Incorrect.

. Change(i.e. material substitution).

. **Construction:** Category used to classify problems caused by the contractor. These problems are not caused by the design team, but solutions to these problems are provided by the design team.

. Error.

. Problems.

Maintenance: A maintenance service exists to keep equipment in running order and also to reduce the number of breakdowns The objective of maintenance is to bring whatever is being maintained towards a state of failure-free operation in construction industry. It includes two stages: construction maintenance and utilization maintenance.

.Operation Error

.Design Error.

.Utilization problems.

Once problems were identified and classified, data were examined for specific relationships and trends to determine if these trends can be used to predict potential problems before they impact the project. It is important to realize that one problem could generate more problems due to dependency. For example, a drawing omission could lead to a procurement problem, which could then cause a schedule delay. These problems were considered indirectly by fuzzy logic in this study

6.5 Results

Preliminary results, which are not presented here, showed that the problems for each unit followed similar trends when examined by problem category and discipline of originator (problem groups). The hypothesis tested was that the percentage of problems for each discipline varied proportionally to the discipline's progress. To test this hypothesis, profile curves were generated similar to those shown in Fig 6-1(Glavan 1988). Three curves depict the possible outcomes. Profile B (straight line) is the 45^0 line expected when the percentage of problems is in proportion to the percentage of a discipline's progress, i.e., problems occur throughout the time the discipline is active on the project and increase at the same rate as the discipline's progress, but have fewer problems at the end of that discipline's activities.

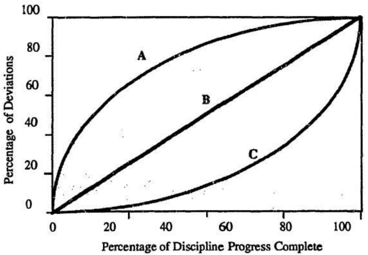
(Note: Complete Structure, refers to the ***structure construction period*** *only).*

Of the three curves, profile ***C*** is potentially the worst case since it shows that problems occur at the end of a discipline's activities. The closer to the end of the construction phase or the beginning of start-up a problem is discovered, the more expensive reworking can become since more disciplines and systems are involved. Also, if management is unaware that a discipline is following a curve-C pattern, there would be no indication that more problems are going to occur until they are actually discovered.

Disciplines that follow curve *A* have a large number of problems that develop quickly, which should bring prompt corrective managerial action. The increased attention lessens their impact.

Disciplines with problems that follow curve ***B*** follow the expected path and do not require the concentrated attention the other two curves usually generate.

Fig 6-1 Example of Profile Curves



(John R. Glavn et. al 1991)

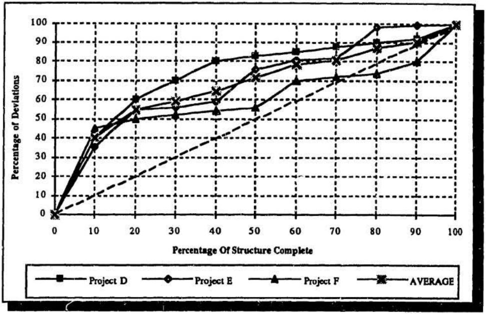
Fig 6-2 to 6-5 show results from the disciplines involved with these projects. Steel structures followed profile **A**, Concrete structure and Flat-plate structure followed profile **B**, Masonry structures followed profile **C**. Design-related problems do not vary during the construction phase of the project. By their nature, the different technologies and complexities of the units caused problems for the design team, but the contractor used existing methods. If the contractor changed technology or procedures would experience more problems. So designers always stress "work follows drawing".

Obviously, the structural problems should be a perfect to fit to a profile **A** curve,i.e., the majority of structural problems should be discovered early —— few occur near the end. One would expect that most of the structural problems should be discovered at the outset of the activity since the determination of excavation depths, foundation locations , form erections, etc., require average information early in the project. One example is the foundation. Accurate information on the location and size must be provided early. Once formed concrete can be poured and finished to specifications without further design guidance.

From the investigation, the problems occur differently for different structures.

Problems with steel structures always happen early in the period of construction. It is close to a curve A fit. While the steel work is being fabricated in the workshop, preparations are going on at the building site. The ground is leveled, obstacles removed, access roads and paths made, and the necessary holding-down bolts embedded in the concrete foundations ready to receive the stanchion bases. Either tall tower erection cranes or jib cranes mounted on high staging are installed, and the 'bits and pieces' of the structure itself are then lifted into place by the steel erectors. The whole sequence of erection has to be programmed to fit in with the work of others on the site. It is one of the advantages of a steel-framed building that the lower stories can be finished off and finished (and sometimes even occupied) while the steel framework is still being erected for the upper stories. But the advantages br' ıg some short comings. Because the installation is a complex process, so in the early stages, a lot of steelworks is transported into a narrow construction site waiting for erection in the correct position. Many workers in the same construction site do different work and to make some mistakes is very easy. Meanwhile, some installation problems are n(t easy to see in a steelworks factory . At the construction site we see them. So in steel structural work one should pay attention to the work that interfaces with installation. See Fig 6-2 for deviation distribution. These can be compared with the three curves shown in figure 6-1 to ascertain which category **A**, **B** , or **C** the type of structure falls into.

Fig 6-2 Steel Structure Discipline



Concrete structures and Flat-plate structures followed profile **B** with only slight deviations. Early deviations (Average line) above the line **B** were similar to the deviations found in the concrete structure discipline; they dealt with foundations and initial layout, near the end of construction problems deviated below the line, which indicated more problems than expected at the end of the activity, since other problems, are caused by the interaction with electrical, plumbing and equipment installation. These become major problems(compared with masonry structure, it is relatively minor). Overall, Concrete and Flat-Plate structure follow profile **B** in that problems increase uniformly as the discipline's progress increases. See Fig-6-3 and Fig- 6-4.

Fig 6-3 Concrete Structure Discipline

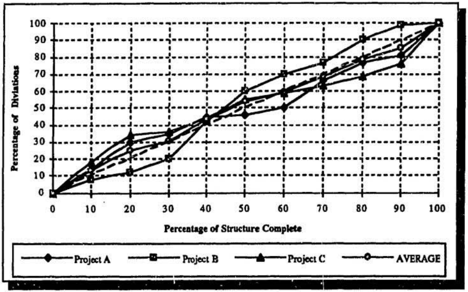
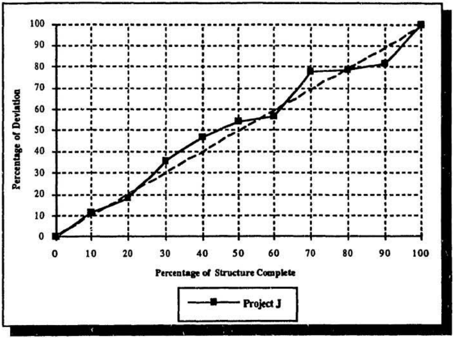


Fig 6-4 Flat-Plate Structure Discipline



The masonry structure follows curve C. The majority of masonry structural problems are discover in the later stages — few occur near the beginning. This is the worst case since problems are only discovered towards the end. When problems are discovered late, the cost of correcting them is much greater than if corrected early on. More work has been completed and consequently rework becomes much more complex and involving more systems. The masonry structure relies on the wall to support the load of the building and equipment. The problems often occur during the installation period due to equipment etc. Masonry structure is not like frames structure and steel structure. During equipment installation, if you want to make some changes without damaging masonry walls, it is almost impossible. See the Fig 6-5 for cumulationve distribution.

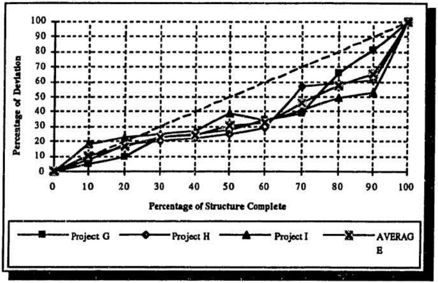


Fig 6-5 Masonry Structure Discipline

6.6. Using Fuzzy Relation Data-Base(FRDB) Method To Forecast The Design Deviation And Man-Hour

The above study provided an excellent record of the time and deviations. The results were consistent for all four units of this project; therefore, models were developed using regression analysis to predict the number of problems that might be expected for each discipline. Br: we have to understand that the deviations are uncertain, or vague, and different structure style, different architectural style, different maintenance systems influence each other. So we can use fuzzy logic method to solve these problems.

methodology to assist managers to predict design deviations and Man-hours in design and construction. The basic idea is to use a composite procedure to set up a fuzzy relation set of the projects, and then use the fuzzy relation set to get the Weights coefficients of the projects. One then normalizes the Weights coefficient to get the degree of complexity of the whole project. Finally considering the degree of complexity, deviations, and man-hours, a regression method can be used to obtain the forecasting equations.

[1]. Determination of Weights Evaluating Set X:

Weights Evaluating Set X are composed by weights evaluation factors. Weights evaluation factors express how we evaluate the weight of influence of different factors in one project.

$$X = \{ x_1, x_2, \ldots x_n \}$$

say, we use $\widetilde{A}$ for building attributes instead of X. If we want to evaluate a building, we consider its architectural style, structural style, and maintenance system. Experts can evaluate the complexity of each of these attributes. These evaluations allow one to define the weights evaluation factors a_1, a_2, a_3 which should be normalized to add up to 1. Hence, the Weights Evaluation set $\widetilde{A}$ is :

$$\widetilde{A} = \{ a_1, a_2, \ldots a_n \}$$

(i.e. a_1 = Architectural style = 0.3,

a_2 = Structure style = 0.6 ,

a_3 = Maintenance style =0.1)

$$\widetilde{A} = (0.3,\ 0.6,\ 0.1)$$

[2.] Determination of Fuzzy Relation Set ______ $\widetilde{R}$

$$R = \begin{pmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ & \cdots & & \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{pmatrix}$$

r_{ij} is Fuzzy Complexity Factor.

$i = 1,2,\ldots n.\ \ j = 1,2,\ldots m$

The Fuzzy Relation Set $\widetilde{R}$ is a modifier. It reflects the relationship of Fuzzy set $\widetilde{A}$ and $\widetilde{B}$. $\widetilde{R}$ consists of Complexity Factors. With the help of Fuzzy Relation Set $\widetilde{R}$, we can calculate how the different technical complexity factors' influence each other. The methodology organizes a problem into the following sequential format: (1) define basic criteria; (2) group basic criteria into progressively fewer, more general groups; and (3) normalize and evaluate the complexity of design and construction projects. The next section explains how the sets $\widetilde{A}$ **and** $\widetilde{B}$ can be conbined to give $\widetilde{R}$.

Composite Procedure

The selection plan contains the weighting procedure used to determine the technical adequacy of each special field and thus form the basis for making an award. It lists the basic criteria of the technical feature to be evaluated, the inputs of basic criteria, and the salient characteristics of each criterion, and "the expert degree of complexity".

(The expert degree of complexity is according to the experts' evaluation. The complexity of a project can be divided into several " diviations degrees. See Tables 6-1, 6-2, 6-3, 6-4).

The composite procedure involves a step-by-step regrouping of a set of various basic criteria to form a single criterion . The 27 basic criteria shown in Table 6-1 are selected as critical and sensitive criteria in accordance with the evaluation criteria specified in the request for degree of complexity evaluation from experts. In this study, the Degree of Complexity (as shown in Table 6-2) specified by the author's experience and some expert's suggestions. It divied into three degrees. The first level is NORMAL, that refers to the work in Construction or design that is relatively not too easy and not too hard to be completed. The second level is COMPLEX, this refers to this work that is relatively harder than NORMAL condition. The third is VERY COMPLEX, this refers to work which is very difficult to do. This is the definition selected for the projects which were investigated by the author. See Table 6-1 and Table 6-2 .

Table 6-1 The Definition of Complexity Degree

Intensity of complexity	Definition
0-1	Normal
1-2	Complex
2-3	Very Complex
0.5,1.5, 2.5	Intermediate degree

Table 6-2 Example of Composite Procedure

Third Level	Second Level	First Level	Degree of Complexity
Construction	Architecture Style	Residential	1
		Industry	2
		Public	3
	Structure Style	Steel	1
		Concrete	2
		Masonry	3
	Mechanical/ Electrical system	Equipment	1
		Communication	2
		Heating and Light	3
Design	Architecture Style	Industry	1
		Residential	2
		Public	3
	Structure Style	Masonry	1
		Concrete	2
		Steel	3
	Mechanical/ Electrical System	Heating and Light	1
		Plumbing System	2
		Power System	3
Maintenance	Architecture Style	Industry	1
		Public	2
		Residential	3
	Structure Style	Steel	1
		Concrete	2
		Masonry	3
	Mechanical/ Electrical System	Heating and Light	1
		Plumbing System	2
		Power System	3

The Table 6-1 shows the complexity of each criteria. The set of basic (first-level) criteria is grouped into a smaller subset of second-level criteria. For example, the basic criteria such as steel structure, concrete structure, masonry structure can be grouped into Structure style, which is an element of the subset of second-level criteria. The same way of grouping is used to form other second-level criteria such as Architecture style, Mechanical;/Electrical system. Further, second-level criteria such as Architecture style, Structure style, Mechanical/Electrical system, are separately grouped into Construction factor, Design factor, Other factor, an element of the subset of third-level criteria. The final composite (system) criterion can be formed by composing the third-level criteria such as Construction and Design and Maintenance factors. Finally, we normalize all factors, and the result is the Fuzzy Relation Set R (matrix).

(3) Determination of Weights Coefficients

Weighting coefficients are assessed to reflect the relative importance of each criterion. To calculate the weighting coefficient, the procedure developed by Kandel (1986) and Z.X. He (1992) is applied. The procedure, can be used to obtain the complexity factor of each criterion in a group based on a paired comparison of each. In this study, we just depend on "expert evaluation" (Table 6-1 and Table 6-2), from past experience and different specialization, we can the get different weight coefficients.

1. Define Fuzzy Evaluation Set

$X = \{ x_1, x_2, \ldots x_n \}$

(x_i = evaluation item, $i = 1,2,3, \ldots n$)

2. Define evaluation language set

$Y = \{y_1, y_2, \ldots y_m\}$

$r_{11}x_1+r_{21}x_2... +r_{n1}x_n = b_1$

$r_{12}\, x_1+r_{22}x_2...+r_{n2}\;\; x_n = b_2$

$\vdots$

$r_{1m}\, x_1+\; r_{2m}x_2... +r_{nm}\, x_n = b_m$

The problem is simplified into solving the fuzzy equation set.

$b_1, b_2, ...b_m$ are the weight coefficient factors, they reflect the relative importance of each criterion in the project.

(4). Normalizing Fuzzy Weights Coefficient Set $\tilde{\mathbf{B}}$, then we can get the relative complex degree of each item.

In this research , we use ten project (Table 6-3) to calculate the degree of complexity of each item.

TABLE 6-3. Descriptions of Projects Studies

PROJECT	TYPE OF STRUCTURE	TYPE OF USE	TOTAL INSTALLED PROJECT COST(RMB)
A	Concrete Frame	TECHNICAL	90,000,000
B	Concrete Frame	HOSPITAL	20,000,000
C	Concrete Frame	WORKSHOP	30,000,000
D	Steel Structure	RESIDENTIAL	12,500,000
E	Steel Structure	OFFICE	234,000,000
F	Steel Structure	FACTORY	19,000,000
G	Masonry Structure	RESIDENTIAL	7,500,000
H	Masonry Structure	RESIDENTIAL	10,900,000
I	Masonry Structure	HOTEL	65,000,000
J	Flat-Plate	COMMERCIAL	76,900,000

(i.e. y_i = Good, Very Good, ...)

3. We use Single factor evaluation . That is, set up a fuzzy mapping set from X to Y, and get the fuzzy relation set R. R is the single factor evaluation matrix

$$f: X \rightarrow F(Y)$$

$$X_i \rightarrow r_{i1}/y_1 + r_{i2}/y_2 + \dots + r_{im}/y_m$$

$0 \le r_{i1} \le 1 \quad i = 1,2,\dots n \; j = 1,2,\dots m$

because $$\tilde{R} = \begin{pmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ & \cdots & & \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{pmatrix}$$

If we let evaluation set $X = \{ x_1, x_2, \dots, x_n \}$, R is fuzzy relation matrix, so

$$\tilde{X} \circ R = \tilde{B}$$

$$(X_1, \; X_2, \; \cdots, \; X_n \;)^{\circ} \begin{pmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ & \cdots & & \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{pmatrix} = (\; b_1, \; b_2, \; \cdots, \; b_n \;)$$

According to Zadeh (1965), we get

$(r_{11} \wedge x_1) \vee (r_{21} \wedge x_2) \vee \dots \vee (r_{n1} \wedge x_n) = b_1$

$(r_{12} \wedge x_1) \vee (r_{22} \wedge x_2) \vee \dots \vee (r_{n2} \wedge x_n) = b_2$

$\vdots$

$(r_{1m} \wedge x_1) \vee (r_{2m} \wedge x_2) \vee \dots \vee (r_{nm} \wedge x_n) = b_m$

{Note($\vee$) , ($\wedge$) Minimum (Maximun) of fuzzy numbers by max-min convolution}

If we use "+" instead of "$\vee$" and "•" instead of "$\wedge$" , then we can get equations

For example, how to obtain the degree of complexity of Project A:

(1) Choose Weights Evaluation factor's domain:

U = { Architectural style, structural style, mechanical/ electrical system}

(2): Determining evaluation term set

V= { Design factor, construction factor, Maintenance factor)

(3) Fuzzy relation Factors:

Design factor:

From table 6-1 and Table 6-2, we can get Architecture style is Public,

degree of complexity is = 3,

the structure style is concrete, degree of complexity is = 2,

Mechanical /Electrical system style is heating and Light, so degree of complexity is 1.

So its Design factor should be

$$DF = \begin{bmatrix} 3 \\ 2 \\ 1 \end{bmatrix} = \begin{bmatrix} r_{11} \\ r_{21} \\ r_{31} \end{bmatrix}$$

Construction Factor: (CF)

From Table 6-1 and 6-2, in the construction part,

the architecture style is public, the degree of complexity is 3, the structure style concrete frame, so its degree of complexity is 2,

the Mechanical /electrical degree of complexity is 3 ; so the degree of complexity of Construction factor CF should be

$$CF=\begin{bmatrix} 3 \\ 2 \\ 3 \end{bmatrix}=\begin{bmatrix} r_{12} \\ r_{22} \\ r_{32} \end{bmatrix}$$

<u>**Maintenance Factor :(MF)**</u>

Architecture style is Public , but its maintenance is a little more complex, so

its degree of complexity is 1.5,

the structure style is concrete, degree of complexity is = 2,

Mechanical /Electrical system style is heating and Light, so degree of complexity is 1.

So Maintenance Factor (MF) should be

$$MF=\begin{bmatrix} 2 \\ 1 \\ 3 \end{bmatrix}=\begin{bmatrix} r_{13} \\ r_{23} \\ r_{33} \end{bmatrix}$$

(4) Weights Evaluation Factor:

We choose the weighting evaluation factor as follows:

Architectural style (AS) 0.3

Structural style (SS) 0.6

Mechanical /Electrical system (ME) 0.1

thus $\widetilde{A} = [\, 0.3,\ 0.6\ ,\ 0.1\,]$

$$\begin{array}{cc} & \begin{array}{ccc} DF & CF & MF \end{array} \\ R = & \begin{bmatrix} 3 & 3 & 1.5 \\ 2 & 2 & 1 \\ 1 & 3 & 3 \end{bmatrix} \end{array} \begin{array}{l} \\ \text{(Architectural Style)} \\ \text{(Structural Style)} \\ \text{(Mechanical/Electrical System)} \end{array}$$

To normalize every horizontal line, we get

$$R = \begin{bmatrix} DF & CF & MF \\ 0.40 & 0.40 & 0.20 \\ 0.40 & 0.40 & 0.20 \\ 0.14 & 0.43 & 0.43 \end{bmatrix}$$

so $\widetilde{A} \circ R = \widetilde{B}$

$$\begin{array}{c} AS\ SS\ ME \\ \begin{bmatrix} 0.3, 0.6, 0.1 \end{bmatrix} \end{array} \circ \begin{bmatrix} DF & CF & MF \\ 0.40 & 0.40 & 0.20 \\ 0.40 & 0.40 & 0.20 \\ 0.14 & 0.43 & 0.43 \end{bmatrix} = \begin{array}{c} DF\ \ CF\ \ MF \\ \begin{bmatrix} 0.40, 0.40, 0.20 \end{bmatrix} \end{array}$$

To normalize $\widetilde{B}$, so 0.4+ 0.4 + 0.20 = 1.

So DF = 0.40/1.0 = 0.4

$CF = 0.40/1.0 = 0.4$

$MF = 0.20/1.0 = 0.20$

So the final weighting coefficient is $DF= 0.4$, $CF = 0.4$, $MF = 0.2$

We multiply all weighting coefficients by 10, and regard them as The Degree of complexity of the Project. Hence we can get the Table 6-4

Table 6-4 The Degree of Complexity List

PROJECT	TYPE OF STRUCTURE	TYPE OF ARCHITECTURE	DESIGN DEGREE OF COMPLEXITY (X 10)	CONSTRUCTION DEGREE OF COMPLEXITY (x 10)
A	Concrete Frame	Public	4	4
B	Concrete Frame	Public	3	4
C	Concrete Frame	Industry	4	5
D	Steel Structure	Public	3	2
E	Steel Structure	Public	8	2
F	Steel Structure	Industry	7	1
G	Masonry Structure	Residential	1	5
H	Masonry Structure	Residential	2	6
I	Masonry Structure	Public	2	7
J	Flat-Plate	Public	3	5

It is realized that the process complexity and the actual detailed design complexity are separate issues. However, due to the small sample size available and the limitations of the documentation, complexity was considered as one variable. Therefore, the independent variable used in the regression analysis was the number of design man-hour, and the dependent variable used was the number of problems.

Table 6-5 shows the number of design man-hours for each discipline and Fig 6-6 show the plot of the number of problems versus number of design man-hours. It appears that as the technology of a unit moves from a mature technology to the newest technology the number of problems and the number of design man-hours for each discipline increases. This holds true even for Steel structure although the amount of steel structure design man-hours is so much greater than that for other disciplines. The slope of these lines indicates that an increase in complexity of a project increases design man-hours for a given technology. Increasing design man-hours further should result in the design deviation being decreased, but reach minimum with a specific number of design man-hours. Realistically, it is known that zero deviations could not be reached and that there is a practical lower limit. Generally speaking, the designer should control the design problems so that they are as close to the optimum deviation level, as possible.

As complexity increases, so does the design effort and, potentially, the number of problems; and at a certain level of technology, an increase in the number of design man-hours should reduce the number of design-related problems. A study of more projects, especially projects with different designers-constructors in teams, as well as an attempt to isolate variables that would predict the results, such as designer's experience, workload, design schedule, etc., would have to be undertaken before definite conclusions could be drawn concerning the benefit of increasing the number of design man-hours to reduce design-related problems.

TABLE 6-5

THE NUMBER OF DESIGN MAN-HOURS FOR EACH DISCIPLINE

Project	Degree of Complexity	Concrete Frame (ManHours/100m^2)	Steel Structure (ManHours/100m^2)	Masonry Structure (ManHours/100m^2)	Flat-Plate Structure (ManHours/100m^2)
A	4	4.85	-	-	-
B	3	3.54	-	-	-
C	4	5.03	-	-	-
D	3	-	3.85	-	-
E	8	-	8.07	-	-
F	7	-	7.24	-	-
G	1	-	-	1.33	-
H	2	-	-	2.12	-
I	2	-	-	2.39	-
J	3	-	-	-	3.47

Design Man-Hour And Complexity Calculation:

Table 6-6 shows the degree of complexity and design Man-hours relation. We can use it to get a numerical equation.

TABLE 6-6 THE DEGREE OF COMPLEXITY OF PROJECTS VERSUS DESIGN PROBLEMS AND MAN-HOUR

Project	Y(Man-hour/100m^2)	X(Degree of Complexity)	Design Problems(/100m^2)
A	4.85	4	4.6
B	3.54	3	3.8
C	5.03	4	4.2
D	3.85	3	4.3
E	8.07	8	7.3
F	7.24	7	5.9
G	1.33	1	2.1
H	2.12	2	2.5
I	2.39	2	2.1
J	3.47	3	3.2

let X = the design degree of complexity of project, y = the design Man-hours(/100m^2) . We have the following results of statistical analysis:

x	x^2	y	y^2	xy
1	1	1.33	1.77	1.33
2	4	2.12	4.49	4.24
2	4	2.39	5.71	4.78
3	9	3.54	12.53	10.62
3	9	3.85	14.82	11.55
3	9	3.47	12.04	10.41
4	16	4.85	23.52	19.40
4	16	5.03	25.30	20.12
7	49	7.24	52.42	50.68
8	64	8.07	65.12	64.56
Sx=38	Sx^2= 181	Sy=41.89	Sy^2=217.74	Sxy=197.69

$Y = S\,y\,/\,n = 41.89\,/10 = 4.19$

$X = S\,x\,/\,n = 38\,/10 = 3.8$

$Lyy = S\,y^2 - n(Y)^2 = 217.74 - 10 * (4.19)^2 = 42.26$

$L_{xx} = S\,x^2 - n(X)^2 = \; 181 - 10 * (3.8)^2 = \; 36.6$

$L_{xy} = S\,xy - n(xy) \; = 197.69 - 10 * (3.8 * 4.19) = 38.37$

Regression Coefficient ***b***:

$b = L_{xy}/\,L_{xx} = 38.47/36.6 \; = 1.05$

Regression Coefficient **a**:

$a \; = Y - bX = 4.19 - 1.05 * 3.8 = +0.2$

hence : $y=a+bx$

$y =$ 1.05x+0.2.................................(equation 6-1)

where y is the design Man-hour($m^2/100$), x is the design degree of complexity of project

The equation expresses the relationship between the design manhours and design degree of complexity.

Checking:

From equation 3-1:

$$R = \frac{L_{xy}}{\sqrt{L_{xx}L_{yy}}}$$

$$= \frac{38.47}{\sqrt{36.6 \times 42.26}} = 0.978$$

Since R $= 0.978$ $\quad R^2 = 0.96$

So

$$t = \frac{R\sqrt{n-2}}{\sqrt{1-R^2}} = \frac{0.98 X \sqrt{8}}{\sqrt{1-0.98^2}} = 13.84$$

Since t= 13.84 > > $t_{0.025,8}$ = 2.306 (confidence level is 95%)

hence, we can think of the equation as being positively related to the data.

In the same way , we can get the relationship between the Design degree of complexity and the design deviations:

let x= Design degree of complexity and z= deviations of design(/1000m^2), we have

x	$x2$	Z	Z^2	xZ
8	64	7.30	53.29	58.4
7	49	5.90	34.81	41.30
4	16	4.60	21.16	18.40
4	16	4.20	17.64	16.80
3	9	3.80	14.44	11.40
3	9	4.30	18.49	12.90
3	9	3.20	10.24	9.60
2	4	2.50	6.25	5.00
2	4	2.10	4.41	4.20
1	1	2.10	4.41	2.10
$S\ x$ =38	$S\ x^2$ = 181	$S\ Z$ = 40.00	SZ^2=185.14	S_{xz}=180.1

$X = S\ x/\ n = 38/10 = 3.8$

$Z = S\, z / n = 40.00 / 10 = 4.00$

$Lxx = S\, x^2 - n(X)^2 = 181 - 10 * (3.8)^2 = 36.60$

$Lzz = S\, z^2 - n(z)^2 = 185.14 - 10 * (4.00)^2 = 25.14$

$Lxz = S\, xz - n(xz) = 180.10 - 10 * (3.8 * 4.00) = 28.10$

Regression Coefficient ***b***:

$b = Lxz / Lxx = 28.1/36.6 = 0.77$

Regression Coefficient **a**:

$a = Z - bx = 4 - 0.77 * 3.8 = 1.07$

hence

$Z = 1.07 + 0.77X$ .... (equation 6-2)

The equation 6-2 expresses the relationship between design degree of complexity and design deviations.

Correlation Coefficient

$R = 0.93$, $R^2 = 0.86$

$t = 7.03 >> t_{0.025} = 2.306$

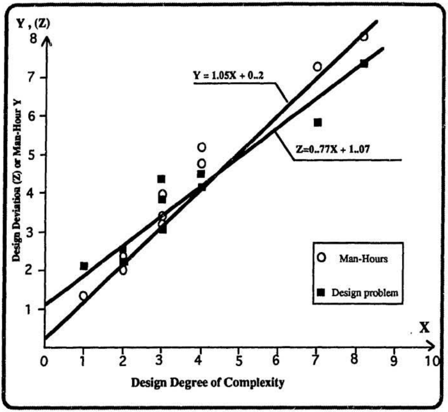


Fig 6-6 Design Degree of Complexity VS Design Deviations or Man-Hours

Conclusions from this analysis are:

1. Regression equation 6-1 explains 96% of variability in design Manhour/100m^2 of design degree of complexity. Equation 6-2 explains 86% of variability of design deviations as a function of design degree of complexity.

2. The model is statistically significant at α =5%

3. Results show that using the two equations (6-1 and 6-2) we can forecast the design deviation if we know the design degree of complexity.

An example of how to use the regression equation to predict the number of design-related deviations when the design degree of complexity is known is as follows:

Given the design architectural style , and structural style, and other transportation situations, we can use Table 6-3 to get the design factor, after that we can get the weighting coefficients. Then we can get the design degree of complexity . Then using equations 6-1 and 6-2 to forecast the deviations and man-hours in designing.

6.7 Forecasting Construction Man-Hours And Deviations Using Construction Degree Of Complexity

We can forecast the number of construction deviations and Man-hours by using construction degree of complexity as the independent variable. Table 6-7 show the number of construction man-hours for each project.

Table 6-7 Construction complex degree and Man-hours list.

PROJECT	Construction Degree of Complexity	Construction Man-hour/(m^2)	Construction Deviations/(1000m^2)
A	4	1.85	3.47
B	4	2.52	2.16
C	5	3.13	1.54
D	2	1.33	3.28
E	2	1.41	3.91
F	1	1.21	4.11
G	5	3.43	1.78
H	6	3.81	1.9
I	7	4.89	1.59
J	5	3.58	1.2

Let x_c = Construction degree of complexity, y_c = the Man-hours of construction. We can get

x_c	x_c^2	y_c	y_c^2	$x_c y_c$
1	1	1.21	1.46	1.21
2	4	1.33	1.77	2.66
2	4	1.41	1.99	2.82
4	16	1.85	3.42	7.4
4	16	2.52	6.35	10.08
5	25	3.13	9.80	15.65
5	25	3.43	11.76	17.15
5	25	3.58	12.82	17.9
6	36	3.81	14.52	22.86
7	49	4.89	23.91	34.23
Sx_c=40	**Sx_c^2= 201**	**Sy_c= 27.16**	**Sy_c^2 = 87.80**	**Sz_cy_c = 131.96**

$Y_c = S\, y_c / n = 27.16 / 10 = 2.716$

$X_c = S\, x_c / n = 40 / 10 = 4.0$

$L_{ycyc} = S\, y_c^{\,2} - n(Y_c)^2 = 87.80 - 10 * (2.716)^2 = 14.03$

$L_{xcxc} = S\, x_c^2 - n(X_c)^2 = 201 - 10 * (4)^2 = 41$

$Lxcyc = S\, x_c y_c - n(x_c y_c) = 131.99 - 10 * (4 * 2.716) = 23.35$

Regression Coefficient ***b***:

$b = Lxcyc / Lxcxc = 23.35/41 = 0.57$

Regression Coefficient ***a***:

$a = Y_c - bX_c = 2.716 - 0.57 * 4 = +0.436$

hence : $y_c = a + bx_c$

$Yc = 0.57Xc + 0.436$ .... (Equation 6-3)

Equation (6-3) expressed the relationship between construction Man-hours and degree of complexity construction.

Checking:

Since R = 0.97 $R^2 = 0.95$

so t = 12.01

Since t= 12.01 >> $t_{0.025,8} = 2.306$ (confidence level is greater than 95%)

So we can see that the Man-hours of construction are positively related to the data.

In the same way , we can get the relationship between the construction degree of complexity and the construction deviations:

Let x_c = the construction degree of complexity and Z_c= construction deviations (/1000m²), we have statistical result as follows:

x_c	x_c^2	z_c	z_c^2	$x_c z_c$
1	1	1.2	1.44	1.2
2	4	1.54	2.37	3.08
2	4	1.78	3.17	3.56
4	16	1.59	2.53	6.36
4	16	1.9	3.61	7.60
5	25	2.16	4.67	10.08
5	25	3.28	10.76	16.60
5	25	3.91	15.29	19.55
6	36	3.47	12.04	20.82
7	49	4.11	16.89	28.77
S x_c=40	S x_c^2=201	S z_c=24.94	S z_c^2= 72.76	S $x_c z_c$=118.14

$Z_c = S\ x_c / n = 24.94 / 10 = 2.494$

$X_c = S\ x_c / n = 40.00 / 10 = 4.00$

$Lxcxc = S\ x_c^2 - n(X_c)^2 = 201 - 10 * (4)^2 = 41$

$Lzczc = S\ z_c^2 - n(Z_c)^2 = 72.76 - 10 * (2.494)^2 = 10.56$

$Lxczc = S\, x_c z_c - n(x_c z_c) = 118.44 - 10 * 4 * 2.494 = 18.68$

Regression Coefficient b:

$b = Lxczc / Lxcxc = 18.68/41 = 0.46$

Regression Coefficient a:

$a = Z_c - bx_c = 2.494 - (0.46) * 4 = 0.654$

hence

$Z_c = 0.654 + 0.46X_c$ .... **(equation 6-4)**

the equation expresses the relationship between construction degree of complexity and construction deviations.

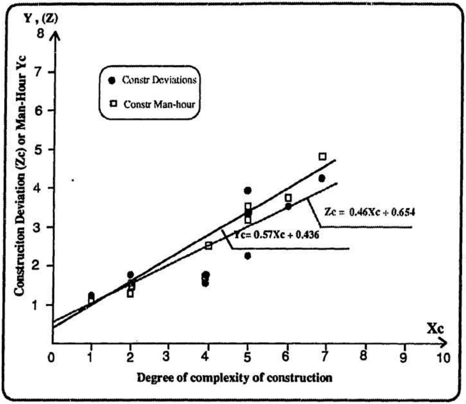
Checking:

Correlation Coefficient

$R = 0.90$, $R^2 = 0.81$

$t = 5.9 >> t_{0.025-8} = 2.306$ (confidence level is greater than 95%)

Fig 6-7. Construction Degree of Complexity VS Construction Deviation or Man-Hours



From above calculation and Fig 6-8 , we know that :

1. Regression equation 6-3 explains 95% of variation of construction man-hours as a function of construction complexity. Regression equation 6-4 explains 81% of construction deviations as a function of construction complexity.

2. All variables are significant at a confidence level greater than 95%

It must be remembered that this data set is very limited. There are only 10 data points. Nevertheless, the trend is there, and early predictions can be approximated using these equations. Further research must be done to validate this model.

Another criticism is the fact that the intercept is not zero which implies that problems exist without any work being done. It must be remembered that regression provides a best -fit line by minimizing the least squares of the residuals, which often includes an intercept. The belief is that the intercept will decrease towards zero with a larger data set; however, in order to provide as accurate an estimate as possible within the limits of the data, the regression equations are recommended for initial use.

The following conclusions are made from this chapter :

1. Design-related problems can be traced back to the design phase of a project.

2. Process and design complexity are one of the causes of design-related problems.

3. Profile curves of different disciplines predict the pattern of problems throughout that discipline's progress.

4. The number of design-related deviations and Man-hours can be forecasted using the design complexity for each project. .

CHAPTER 7. INCREASING DESIGN PRODUCTIVITY

7.1 Introduction

It is appropriate at this stage to consider the means by which productivity may be increased. There are essentially three ways:

1. Work harder.

2. Work smarter (i.e, methods and design improvement).

3. Increase capital investment (e.g. in equipment).

From experience, we know that, most often in design firms, it is not effective to improve productivity by working harder. To work smarter and increase capital investment are far more useful and have led to a number of improvements . Working smart include improving management of the design firm, designer training, and utilizing new and advanced technology, standardization, simplification of representations (work smarter). Investment in improved equipment such as computer aided design systems (CAD) has done much to improve the output capabilities of the draftsman.

Approach 2 is probably the more satisfying ("producing more from less" as opposed to 3 " getting more with which to produce") but the scope for improvement is necessarily limited to some extent and subject to the law of diminishing returns. It is the most inefficient operation which has the greatest room for improvement . This is not to say that improvements from this source have an absolute ceiling. Human ingenuity should always be able to find some ways to improve. Improvements just get harder to find. Hence managers stress design management.

7.2 Management responsibilities:

The emphasis on assuring the quality of design must come from engineering or project management. To be successful, the manager responsible for the engineering work must establish the tone and thrust in policies and practices, and his acts must match his words. It is easy to demand quality when everything is proceeding on schedule, on budget, and is meeting customer requirements.

Periodically, the engineering manager should step back and constructively examine the engineering processes. Do the people in the department know and understand the preferred ways for performing their tasks? Do they actually do it that way? Does the process consistently give the desired results? Are their methods and practices cost-effective?

One useful approach is to select several engineering change notices from some recent projects. Examine these with a critical but constructive eye with the purpose of determining why the change was made. Was it necessary? Was it needed to correct an error or an oversight ? What could have been done differently to avoid the need for the change? What can be done to prevent recurrence?

These ideas are not new. Paulson(1976) stated that the level of influence of value engineering concepts had been well understood in some sectors of industry for many years. The main point of his paper was related to the one made here, namely that the level of influence exercised by management over the cost of a project declines continually as the project proceeds. On day one, management exercises 100% control, i.e. , to build or not to build, each decision from this point onwards reduces the remaining influence over expenditures . The problem, as always , is not with understanding, but with implementation. The difficulty is to achieve a level of acceptance sufficient to motivate the necessary structural changes.

7.3 Design Optimization:

This is really the heart of the matter , and one of the major reasons that the concepts discussed have seen so little in the way of implementation of the concepts outlined in section 4-1 and 4-2. These are absurdly simple, and yet it appears that most engineering projects fail to approach the optimum cost *"o"* point. It must be noted that minimum life cycle cost is not the only possible objective [Moore 1986], but it will serve for discussion here, as the same principles can be applied to any other objectives.

The fact that the design phase is not managed to produce the minimum total life cost is an inevitable consequence of the way the construction industry is structured . It is a consequence, firstly, of the fact that design and construction are treated separately — whether in Canada, United States or China, the costs of the design are negotiated with the consultant in isolation from the costs of construction, and before the design is done. The result is suboptimization during the design phase. This results in many deviations during the construction phase.

The term suboptimization, familiar to operations researchers, refers to the "optimizing "(in terms of some definition) of a small part of a project or process in isolation from the rest, i.e. , there is no integrative thinking, no consideration of the overall picture. We should not be surprised at this. It follows directly from specialization and division of labor, and will always occur unless specific steps are taken to prevent it.

7.4. Communication and feed back in design process

In Chapter 6, we discussed how to forecast the design and construction problems, but it just described the one side of the design quality problem. The other side of the quality problem is a communication problem. Concentrating our attention, for the moment, on the stages in Fig 4-1, some important features can be noted. Firstly, information flows both up and down the chain, to fuel the process. "Design is an iterative process with each iteration aimed at increasing the level of information in order to improve the decision making. Coordination, collection, processing, storage and transmission of information is essential for effective design. Existing information flows should be analyzed to identify bottlenecks and remove them" (Engineering council 1986).

Based on the author's structural design experience, many owners and architect/engineer(A/E) design staffs did not experience an unusually high number of design quality problems. However, they were curious about these problems, and studied the causes to see if they could be addressed. Many of these structural problems could have resulted in more serious failures than those actually encountered, had the situations or settings been different. In any case, such problems did result in a loss of function or production, additional expense for remedial work, nuisance work for the owner's management, and loss of confidence in the design professionals involved.

A subcommittee of the U.S. House of Representatives Committee on Science and Technology held hearings in 1982 to examine the problem of structural failures in the U.S. The subcommittee sought to identify factors that contribute most significantly to the occurrence of structural failure. Its report lists significant factors that are important in preventing structural failures, including these six critical factors: (1) communications and organization in the construction industry; (2) inspection of construction by the structural engineer; (3) general quality of design; (4) structural connection design details and shop drawings, (5) selection of architects and engineers; and (6) timely dissemination of technical data (U.S. Congress 1983). Note that items 1 and 6 are communication -related factors.

In light of this, the gulf between design and construction across which information flows only with difficulty is a glaring anomaly. This gulf, resulting from the traditional separation of the design and construction phases is a consequence of the structure of the construction industry. From Fig 5-3, we know that the main reason that influence design deviations are five factors: owner change (18%), design error (19%), construction requirement(10%) , design improvement (9%), fabrication error (15%). So many scholars and researchers think the best bridge to cross this gulf is to set up an effective communication systems. The basic communication system can be depicted as I have shown in Fig 7-1.

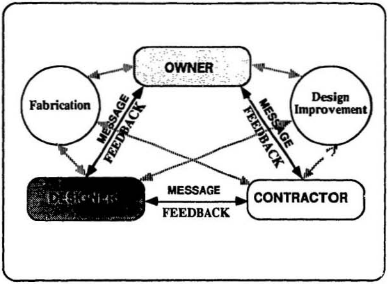


Fig 7-1 Basic Communication System in Construction Industry

This system involves the owner, designer and constructor the three parties in one information system, delivering messages to each other through communication channels. The most important step is "feed back". Unfortunately, for a long time, people put the attention on how the designer delivered information to the constructor, but did not pay attention to constructor's feedback to the designer and owner. In fact, the communication must go both ways.

Feedback refers to information transmitted by a receiver back to the original sender of a message. Feedback can be written, spoken, or conveyed through body language. Many communication experts believe that "true communication " cannot take place until the sender has received confirmation from the receiver that the message has been understood and guaranteed (Boone al. et. 1992)

In practice , owing to failure of communication, many accidents happen. It should be stressed that not only is information sent by designers, but also to get the feedback from the constructors is important. For instance, the failure mechanisms involved in such problems included design errors, unconstructable designs, unanticipated loading, vibration from equipment, vibration from wind vortices, rapid corrosion of structural members, unanticipated high temperatures, unanticipated thermal movement, snow loads in excess of code, water loads in excess of design loads, construction from preliminary drawings, field construction errors, field changes to designs, vague vendor drawings, incorrect vendor information, fast tracking(too fast), and communications, particularly with designer errors and communication/coordination failures. Therefore , some mechanism is required to get the contractor involved in the decision process at the design stage. This will increase the benefit from the feedback loops at a stage where no costs are being increased at the side for correction or modification of the design. Relatively minor modifications at the design stage can lead to major savings in costs at the construction stage. This will also eliminate a lot of construction changes during the construction period. Hensey(1987) investigated over forty failures and accidents in construction. He claimed that about 25% of structural problems are due, in part, to communication /coordination failures. Most of these structural problems could have resulted in serious, life-threatening structural failures under different conditions of loading or had they gone unnoticed for a longer time. For the most part, these problems did not result in serious, life-threatening structural failures , but under different conditions of loading, or had they gone unnoticed for a longer time, they could have. For the most part, these problems were not the result of new technology, technical incompetence, or truly unknown loading, but rather of a communication/coordination breakdown.

7.5. Computer Aided Design (CAD)

Computers can greatly improve the design productivity, as Figure 7-2 shows (Applied Research of Cambridge Limited (ARC)). This figure shows how, with computer-aided design, the greatest amount of time and resources is put into design effort and relatively little into preparation of construction documents. Note how the curve of the right decision of Figure 7-2 compares with ARC's traditional method and how, with computer-aided design, the ability to make the right decisions over a longer period of time is enhanced because of the level of effort put out during the schematic design phase. From the author's experience, CAD can increase design efficiency by at least three to five times. This leads to substantial savings in money and time. So CAD is a valuable investment in the design office.

These gains are valuable, and should be welcomed, as long as they do not obscure the fact that the real problem, and the area of greatest percentile gains, lies elsewhere. This conclusion follows from the fact that there is much more to design than merely putting lines on paper. It is only the last step of a much more difficult process, namely that of deciding what to draw. So the architects and engineers can have more and more time to think and adjust which plan is better or which method is more suitable to the project.

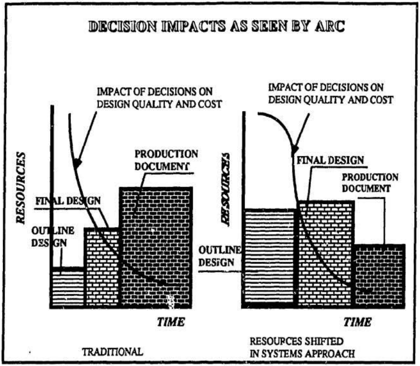


Fig 7-2 Decision Impacts As Seen By ARC (FAIA 1980)

On the other hand, computers can also create problems. Engineering software presents many new challenges. Often, the construction and constraints of the programs have low visibility, coupled with limited user documentation. This is especially true when using software which was developed outside the company. Yet , a strong tendency for engineers is to give the software developers the benefit of the doubt and to use the software somewhat blindly. Again, it is quite easy to misapply computer software, to use it beyond its proven limits, or to make assumptions about it that differ from those made by the software developers. The key for management is to insist that your engineers study the software documentation carefully and apply it with caution. Otherwise, you may have a disaster in the making . In my design firm, at least 10% of accidents were caused by computer related errors.

7.6 Control of Changes and Nonconformances

To be successful, engineering departments must manage change, change must not manage engineering departments. A planned and orderly process is required for defining the change, evaluating its impact, and implementing the details. If anything can go wrong in engineering, it will do so in the change process.

The greatest enemy of the control of change is the pressure of time. Many errors are committed in the name of expediency. Changes often must be acted on quickly, but not haphazardly. Is each engineering change clearly documented? Have all aspects of the change been defined? Are changes reviewed and approved in a manner consistent with the release of the original design? Has the change and its impact been reviewed by technically knowledgeable personnel? Is the change really necessary?

These same questions apply as well to control of nonconformances. Keep in mind that nonconformances are simply unplanned changes. Consequently, their impact must be identified and evaluated and decision must be made in a logical fashion to use, revise, or replace.

7.7 Designers' responsibility during Construction.

As a project reaches the construction phase , the design engineer must define his level of continuing responsibility. The designer should outline the construction standards appropriate for the project and remain involved during construction to the extent necessary to assure these standards are met. In addition, the engineer should prescribe a quality control program and identify the required qualified inspection personnel. The engineer should organize the team that is to implement the program under his/her direction. Unfortunately, this may not often be realized. Sometimes the owner is unable or unwilling to fund inspection efforts and may rely on self-supervision or control of inspection by the specialty contractor. This can and usually does lead to serious fragmentation of responsibility among the owner, architect, design engineer the geotechnical consultant, the general contractor and specialty contractors.

7.8 The responsibility of construction management during design

The responsibilities of construction management in design can be considerable, and are the result of the need to achieve more efficient , realistic designs which take advantage of the skills of construction professionals. Such knowledge should be provided in the early phases of a project, where the most significant savings can be realized.

Construction managers' responsibilities can entail the following(Conner 1983, Holton 1983, Lee 1982, Lindstrom 1982):

1. Design recommendations.
2. Construction contract document packaging and coordination.
3. Cost estimating, budgeting, and controlling.
4. Planning, scheduling, controlling, and coordinating of all project work, including design.
5. Layout of construction site, access, and temporary utilities.
6. On-site construction engineering and management to include processing of changes, payment requests, quality management, surveys and geotechnical investigations.
7. Materials management , including procurement and field materials control.

8. Review of contractor submittals related to field methods to determine compliance with the contract.

9. Responsibility for value engineering.

10. Safety programs.

The above list is not intended to be all-inclusive, but indicate most of the construction management functions having design-related responsibilities. In the design phase, the construction manager performs essentially two roles. This individual assists in the overall formulation of the design by assuming primary responsibility for cost and schedule, and advises the owner or architect/engineer on constructability , and cost and schedule implications of the design.

CHAPTER 8. CONCLUSIONS AND RECOMMENDATION FOR FURTHER RESEARCH

The question of producing better quality designs is obviously a complex one, with implications affecting the whole construction industry. The issues are hotly debated(Richard 1983; Cassino 1983; Zweig 1984), which is an indication of the perceived need for solutions.

(1) Design Quality Greatly Influences Productivity Of Construction.

On the basic of the investigations made in this thesis, the author claims that the low productivity of construction is due to the unsatisfactory quality of design.

(2). Good Design Can Reduce The Cost Of Construction.

Good design at least includes two ideas. One is an economical idea, that is using optimization theory to get the best result in direct cost ; indirect cost; life-cycle cost and the owner's requirement. The second is a technical idea. That is how one can reduce the deviations of design and construction. Design-related problems and construction deviations can be traced back to the design phase and construction of a project. This study shows that the design deviation is the major part of deviation of whole project, so we should pay more effort to improve design quality .

(3). Profile curves of different structure predict the pattern of problems throughout that structure's construction progress.

From this study we can see that different structures in different construction stages have different deviation distributions. Profile curves that tested whether the percentage of problems is linearly proportional to the percentage of the progress complete proved the most insightful. For this case study, the curves showed when problems occurred for each discipline and by examining the procedures and characteristics of each discipline, plausible reasons for the timing of these problems were proposed. If further research shows these curves to be valid for other projects, then management will be able to use them to predict problems and take corrective actions.

(4). The amount of design-related problems and construction deviations can be forecasted using the degree of complexity. Fuzzy logic and statistical methods can be used in forecasting deviations.

Since many design and construction problems are fuzzy, vague and uncertain, it is very difficult using classical (certainty) methods to evaluate these problems only. Furthermore, the author adopted the Fuzzy Relation Data Base system to define the degree of complexity of project, and then to get the weights coefficients. Finally one gets a functional relation between deviation and complexity , man-hours and complexity. After that, using statistical regression method one gets four equations. These four equations of forecasting future problems were proposed. It was observed that the number of problems and man-hours had a strong predictive relationship with the degree of complexity of design and construction. Models were developed for each of these relationship (it must be remembered that the models are used to forecast the problems and not to explain the cause-and-effect relationship). The equations can be used to predict future problems on projects of similar nature. The author claims that, this thesis provide a general approach to forecasting mistakes in design and construction. The author has shown that the timing of deviations will follow a given pattern for a given structure type. This pattern will hold true regardless of who the designer is. The four equations can be changed if relevant data is available. This data should reflect the performance of the designers and managers involved in the projects to be forecasted. Although data are limited, definite trends can be observed and further research using these procedures is recommended. Further investigation could reveal information about the influence that different design and management procedures might have on the number of deviations. The fuzzy logical method used here can be refined as more broadly based data becomes available. It might also be extended to take into account the effect of learning.

(5). Feedback is a good way for improving design quality and productivity.

The structural problems reviewed indicate that quality in the designed and constructed project is not simply a function of the skills and diligence of the various parties involved . It is also a function of their ability to communicate needed information about scope, costs, schedules, technical information, and changes.

There needs to be communication with the contractor at an early stage of the design. The problem is caused again by the system , whereby the contractor is not chosen (in theory) until the design is complete and the bids are in. Vlatas(1986) suggests that the contractor should be brought into the process by the time the design is 30% complete. Again a fundamental change in the way things are done is indicated (where allowed by law).

The role of the construction manager in design must be stressed. In many project design-related activities, such as cost savings, feasibility, and scheduling, the construction manager should play a primary role. Whereas in those functions affecting plant design integrity, the construction role must be advisory. In some field management activities, construction managers actually have design-related responsibilities, and their liability exposure can be considerable.

This study was undertaken by using of the degree of complexity to determine the number of design-related problems that occurred during the construction phase of a project. It is hoped that the cause and impact of these problems could be traced through the existing project documentation. However, the documentation did not provide an estimate of the cost, time , nor the degree of impact that the problems had on the project. Further research into this area will be possible now that this study has shown that design-related problems can be traced back to the design phase of the project and the costs to correct these problems can be monitored.

In summary, the lack of formal techniques and procedures for managing the design process is a hindrance to better quality design. Part of the problem here is the difficulty in evaluating design quality, particularly the correctness of the conceptual design. Unlike measurements of quality and productivity on the construction site there is no standard against which to compare. It is not possible to compare the scheme which was designed with that which was not, nor the design which was built with that which was not. These difficulties arise from the essentially unique nature of each civil engineering project. This does not imply, however, that civil engineering design cannot be measured and evaluated --- it is just more difficult. But Fuzzy logical theory has given us a way of dealing with these problems in the future. This thesis is just a beginning. Combined with statistical methods, this approach may be use to compare the relative efficiencies of different design and management procedures and policies.

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