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TOTAL LIFE-CYCLE CONSTRUCTION (*TLC*)

by

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(ABSTRACT)

The inability of current approaches to the delivery of building systems to manage change is the root cause of significant challenges facing the modern construction industry. These challenges are manifested in the volatile financial status of construction firms, the difficult communications environment and costly professional liability pitfalls facing the industry. *Total Life-Cycle Construction (TLC)* is a revised philosophical approach to the information communication system within the design, delivery and operation of complex building systems and facilities. *TLC* employs the life-cycle principles of Systems Engineering to resolve the organizational challenges which are placing the construction industry at a developmental crossroads.

This project provides a historical overview of the development of the modern construction industry and the problems which are manifesting themselves into the requirement for change. *TLC* develops a revised theoretical information management system for the design, delivery and operation of building systems which exploits current computer technologies.

The *TLC* concept enables the facility development participants to manage change, the root cause of the challenges facing the construction industry as it moves into the twenty-first century.

TLC's theoretical information management methodology applies the life-cycle cost and support principles of Systems Engineering in order respond to the technical and professional challenges of today's construction industry. The concept will enable early identification and mediation of the impact of change on life-cycle facility costs. *TLC* is a hybrid of the design-construction approach to facility delivery, but it incorporates life-cycle cost, support and operational considerations in all decisions. *TLC* is envisioned to employ object oriented three dimensional computer technology augmented by knowledge based systems to infuse life-cycle considerations in a parametric facility design and management tool. *TLC* would enable the generation of a simulated facility prototype for evaluation and modification early in the design life-cycle, thus reducing the financial impact of changes.

The *TLC* facility prototype simulation allows facilities changes to be evaluated or incorporated without the costly delays experienced today by linking dynamic system feedback to object oriented data. Each facility space or object is continually linked to the data which developed it. This allows the prototype to be proactive in identifying and

mediating conflicts. The simulated prototype also yields the data bases required to control construction processes through the common information system. The *TLC* common information base can then facilitate future developments in robotic and automated construction processes.

By applying Systems Engineering life-cycle principles and techniques to the facility design, delivery and operation, *TLC* will improve communication within the construction industry. With improved communication comes the ability to manage change, the root cause of many of the industry's problems. With the common information interaction provided by the *TLC* methodology, the construction industry can evolve into the twenty-first century.

TOTAL LIFE-CYCLE CONSTRUCTION *(TLC)*

ACKNOWLEDGEMENTS

The concepts behind this effort have been developed through the interaction of several people and are the results of the discussion in several graduate courses at Virginia Polytechnic Institute and State University. If not for the particular brainstorming and concept development assistance of Dr Yvan Beliveau and Takis Mitropoulos this paper would not have been possible. I would like to recognize the input and support of my friends and fellow students. Their assistance in brainstorming ideas, research and review significantly improved this project and report. I would like to gratefully acknowledge the assistance of my advisory committee, their recognized expertise, guidance and patience significantly contributed to the preparation of this project and report.

DEDICATION

This project is dedicated in loving memory of my father:

Lieutenant Colonel Richard A Hein, United States Army, 1925-1990

Soldier, Civil Servant, Mentor. Instiller of discipline, dedication, moral courage and professionalism.

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I. INTRODUCTION

"Experience teaches slowly, and at the costs of many mistakes."

- James Anthony Froude[1]

The evolution of the construction industry is as old as the human race; it is a response to the needs, challenges and technologies of the time. Just as with society's evolution, the constructed product is a result of prior experience, mistakes and technical advances. "Construction is a dynamic process that is becoming increasingly complex."[2] This simple statement accurately reflects the environment in which the building system is produced today, and reflects the turbulent history of the means and methods incorporated in and developed for the delivery of building systems. The earmark of this turbulent history has been change, both in terms of technical advances and in the organization under which the built project

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[1]The English Language Institute of America (ELIA), The Living Webster Encyclopedic Dictionary of the American Language, (Chicago, Ill: ELIA, 1975), page BT-72.

[2]Nunnally, S W, Construction Means and Methods, 2nd Edition, (Englewood Cliffs, NJ: Prentice-Hall, 1980), page XV.

is delivered. With change and complexity comes diversity and interdependence, the knowledge and abilities required to erect a major structure today exceeds that of a single individual.

As a result of continuing economic, legal and technical changes, the construction industry of today is modifying its approach to business. Economic considerations require accurate means of planning and managing construction in a highly competitive market. A volatile legal environment is forcing a revised approach to project organization and contractual responsibilities. The high pace technological developments of the last twenty-five years is providing the industry both challenges and tools. Together, these elements are driving the construction industry towards a requirement for a new methodology and approach to delivering the product of the building system.

The interdependent nature of the construction industry's organization has continually changed throughout human history and is at a crossroads today. The construction industry of the year 2000 will be a highly complex interaction of computer controls and robotic processes. A single operator will control the operation and productivity of earthmoving and structural erection equipment in an on-site control booth similar to today's air traffic controllers. Construction will have the ability to be continued twenty-four hours a day and

to take place in currently untenable or hostile environments; climatic extremes, toxic atmospheres and even space. Technologies and interfaces are being developed today which will modify the construction activities and responsibilities of the twenty-first century.[1] To reach this status, the construction industry must recognize and respond to the professional, technical and economic pressures and challenges of today.

Now picture a systems which makes the these futuristic dreams of men like Jules Verne, H G Wells, Isaac Asimov and Ray Bradbury possible. A single computer based system is fed the requirements of a facility; and, then not only generates the plan of the facility, but builds and operates it. This concept is not as far from reality as it seems. With accurate and timely information management the dream of construction in the twenty-first century can be achieved.

1.1 BACKGROUND

Unlike any other animal on earth, mankind spends most of its time in environments of its own creation. The human animal modifies the environment around it to suit its survival

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[1]Bechtel Media Services, Constructs 2000, (Gaithersburg MD: Bechtel, 1990).

requirements, making man the master of harsh environments but a slave to the shelters that are required for survival. This molded, man-created environment, consisting of dwellings, temples, gatherings points and places of commerce, constitutes the system commonly known as architecture. The architecture or building systems of a people reflects the social, economic, spiritual beliefs and lifestyles of the culture. Architecture is used by archaeologists and anthropologists to reconstruct the people who used them.[4] The construction industry has developed with the knowledge, requirements, capabilities and technology of mankind into the means of delivering the building system. The construction industry reflects both the technical complexity of today as well as a response to the mistakes and challenges of the past.

Developments within the construction industry not only measure the cultural environment of the time, but today also predicts future events and trends within the economy. The construction industry is the largest single production industry in America. This means that the construction industry is the country's economic bellwether industry; and that its status significantly affects the nation's economic

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[4]Raskin, Eugene, Architecture and People, (Englewood Cliffs, NJ: Prentice-Hall, 1974), page 3.

health.[5] The construction industry must monitor and establish economic and technical practices to assure success, since it is such a crucial component of the economic system. Unfortunately, in a competitive bidding environment, success is neither easy nor guaranteed for a construction firm; "it is difficult for a contractor to make a profit in competitive bidding when the highest price he can get for a job is the lowest price for which his cheapest competitor is willing to take."[6] This process induces a construction firm to make often hazardously low estimates of project costs, which may not incorporate the actual cost of doing business. When this risky pricing environment is coupled with a front-loaded negative cash-flow for each project, the management of construction projects over their entire life-cycle becomes crucial.

The construction industry is an interaction of a multitude of professional disciplines; architects, engineers and technical tradesmen. The architects and engineers of today are highly educated, technically specialized, registered professionals entrusted with the health, welfare and safety

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[5]Clough, Richard H, Construction Contracting, Fifth Edition, (New York, NY: John Wiley & Sons, 1986), page 3.

[6]Construction Industry Institute, "Contractor Planning for Fixed-Price Construction", (Austin TX: CII, May 1987), page vii.

of society. The construction producer or contractor must translate the concepts of the design professional into an economically feasible and physically stable environment. Through the course of history, the interaction of and communication between these disciplines has been modified with the technology of the times. In more recent times, technology changes have not been the only force in modifying the relationship between these elements. Ethical and legal liability issues have significantly affected the roles and responsibilities of each component in the industry structure.

The future of the industry will be determined by how the organization and tools of the industry will be modified to address the management of change, the root cause of these challenges. One method available to address this complex and divergent organization is the application of the principles of System Engineering, a recognized approach to managing large-scale interdisciplinary problems. The integrated application of basic organizational principles, methodical practices and an interdisciplinary approach to technology over the entire life-cycle of a system is the goal of Systems Engineering.

This paper will propose a theoretical information management methodology for the delivery and operation of complex building systems and facilities which applies the

life-cycle cost and support principles of Systems Engineering and responds to the technical and professional challenges facing today's construction industry. The systems approach to the delivery and operation of facilities has been developed into a theoretical interactive and interdisciplinary information management model called *Total Life-cycle Construction (TLC)*.

1.2 PROJECT SCOPE AND OVERVIEW

This project an report develops and presents a theoretical facility information management model called *Total Life-cycle Construction (TLC)*. *TLC* is the formalized interaction of the requirements, knowledge and products of each the construction industry's participants. The transfer, processing and feedback of information in and between elements of the process throughout a buildings life-cycle (concept through retirement) is vital for the future and development of the construction industry. The development of tools to incorporate and transfer technological advances, disciplinary knowledge and life-cycle requirements will be an integral aspect of this approach.

The *TLC* interaction concept (Figure 1) is a means to exploit the technology of today and the feedback and interdisciplinary principles of Systems Engineering to solve

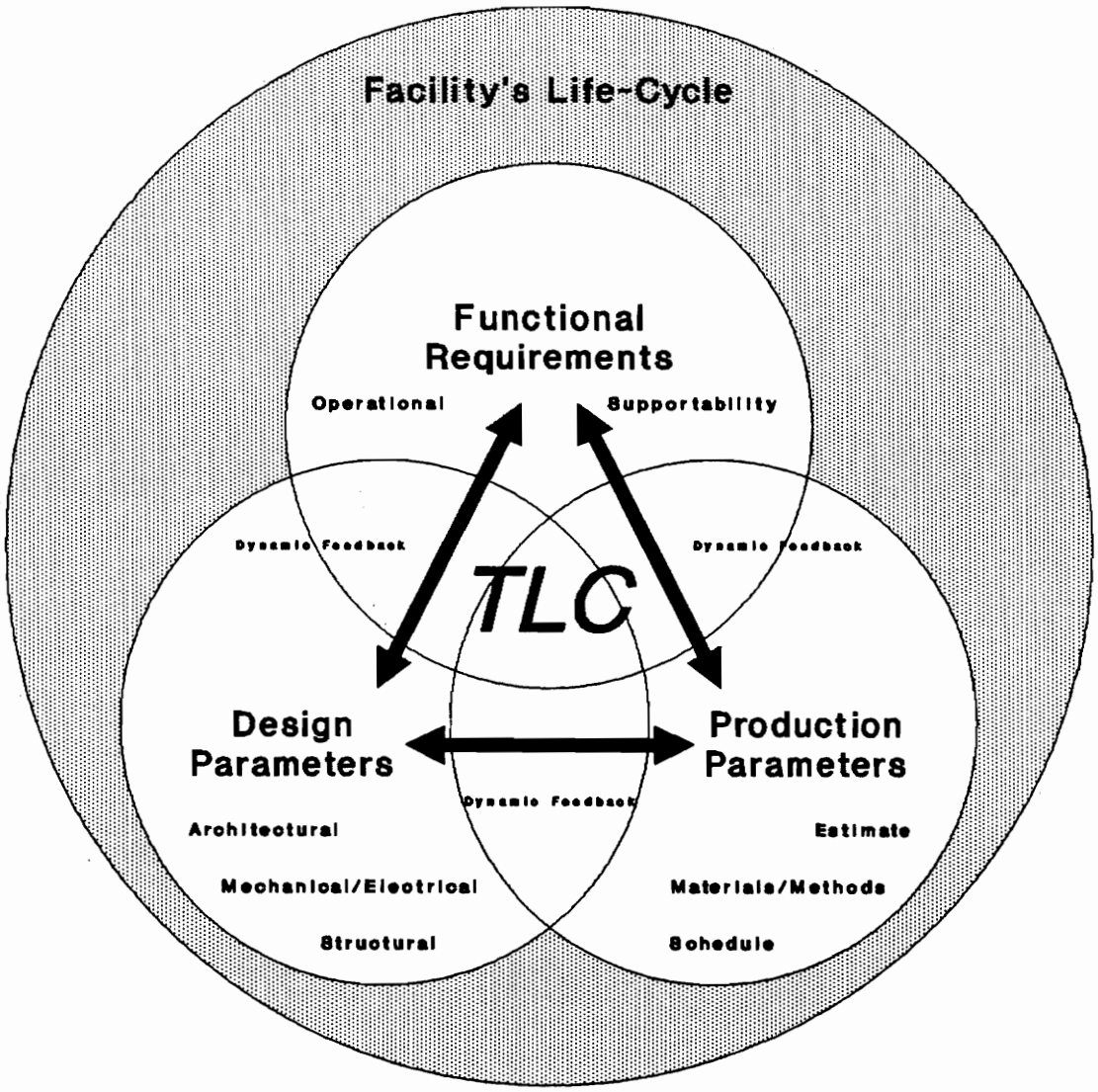

Figure 1: THE *TLC* INTERACTION CONCEPT

the communications and organization problems threatening the construction industry. The concept is designed to assure the full development and interaction of the requirements and concerns of the consumer, the designer and the producer throughout all stages of the building system's life-cycle. This is intended to integrate the knowledge and needs of each of the construction process participants into the decisions of the other participants in a timely manner to reduce overall life-cycle conflicts and costs.

In order to set the stage for the *TLC* development, this project and report will address three of the major concerns facing today's construction industry which constitute the need for a revised approach to building system delivery; the development of the construction process's organization, the financial pressures on the industry, and the technological advances in construction system design and management tools. The project and report will then examine the history and benefits of the Systems Engineering approach to interdisciplinary problem solving before applying these principles to the development of a revised approach to the facility information management process, *TLC*.

In Chapter 2, the historical development of the construction organization is examined. The development of professional and disciplinary relationships is traced from the

Master Builder concept through the *Laissez-faire* Architect of today. The professional liability issues and communication challenges which fostered this increasing detachment of the architect from the construction process are discussed. Alternative approaches to the delivery of building systems are reviewed in terms of the Design-Construct contracting strategy and the Professional Construction Manager.

The financial pressures impacting the construction industry are explored in Chapter 3. The impact of competitive bidding on a firm's profitability is explored. In Chapter 4, the management tools and emerging technology within the construction industry are discussed. The development of network scheduling and bidding models as management tools are reviewed. The current expansive inclusion of computers within the industry is discussed in terms of advances in Computer Aided Design (CAD), knowledge based technology and object oriented data.

Chapter 5 reviews the principles of Systems Engineering and their application within the challenges facing the construction industry. Dynamic system modeling and logistics engineering are integrated with the life-cycle engineering approaches to problem solving. The incorporation of logistics support and life-cycle cost models within the construction process forms the basis for the development of the *Total Life-*

cycle Construction (TLC) information management and communications model. The *TLC* model concept is developed in Chapters 6 and 7 through the application of functional analysis of the design and construction process as well as the facility operational and support requirements following the principles of Systems Engineering.

The resulting abstract communications model is envisioned to enable rapid communications between functional participants within the process of design, delivery and operation of facilities. This communication via three dimensional computer simulations can manage the impacts of change on the life-cycle of the building system. The resulting model is envisioned as an object oriented parametric design tool which will provide the information required for not only design, delivery and operation of facilities, but also for the control of the construction (or facility production) process.

With a common information management system like *TLC*, the construction industry will be able to develop into the envisioned "high-tech" process of the twenty first century. In order to reach this new information management approach to construction it is important to understand how the industry developed into its current configuration.

II. DEVELOPMENT OF THE CONSTRUCTION SYSTEM

"The doctor can bury his mistakes but an architect can only advise his client to plant vines."
- Frank Lloyd Wright[7]

The complexity of the management of construction project has advanced parallel to the technical advances of the industry and the enlarged scope of projects. Tradesmen and builders of the past understood all aspects of their projects; materials and building methods were simple; markets and the scope of a project were small; and technology changed very slowly. As the design, production and management of the facility production process becomes ever more complex, no single participant can grasp the technical or operational requirements of the process. In this chapter the development of the construction industry from tradesmen to fragmented professionals will be examined. The professional issues of responsibility and liability as well as the hazards of complex communication systems will be explored.

From the Mesopotamians through the Industrial Revolution, the means and methods of construction changed and developed very slowly. Buildings of the Machine Age where an explosion

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[7]Byrne, Robert, 1,911 Best Things Anybody Ever Said, (New York, NY: Fawcett Columbine, 1988), page 307.

of technology which allowed increased building size and lead to highly complex components. New systems of lighting, heating and cooling radically altered the complexity of internal building systems, materials and methods of construction. This growth and complexity required the construction industry to modify its organization and practices concurrently with historical and technological advances.

2.1 MAN THE BUILDER

With the development of an agrarian culture, the human animal abandoned nomadic hunter-gatherer lifestyle and therefore dependence on natural shelters. Ten thousand years ago man the farmer also became man the builder.[1] The static lifestyle bred a requirement for a system of producing shelters. As early man gathered together, the building system developed from providing dwellings for shelter to include other structure for the benefit of the group. The skilled craftsman or tradesman developed to deliver the structures, freeing others of the group to produce the other necessities of survival. The structures of early mankind were simple,

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[1]Copplestone, Trewin, World Architecture, (Seacaucus, NJ: Chartwell Books, 1977), page 17.

common and status free.[9]

Through a process of trial and error, the methods and means of construction were developed. Tradesmen began to specialize in various methods delivery structures (masons carpenters, etc). In the third millennium B.C. concurrently in both Malta and southern England (Stonehenge), evidence exists of man the professional builder. The contemporary temples of these distant areas show evidence of parallel technological and craftsmanship developments. "The builders, not content with their initial vision, reformed and amplified it repeatedly."[10] This development of the professional building trades for the delivery of temples would begin a relationship that would continue for centuries. The production of religious structures would provided the framework for developments and technological advances of the construction industry through the industrial revolution.

2.2 MASTER BUILDER

"Nowhere does the close lock between man's concepts and his architecture show itself more clearly than in the design

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[9]Kostof, Spiro, A History of Architecture, (New York, NY: Oxford Press, 1985), page 27-30.

[10]Kostof, page 32.

of churches, temples, cathedrals-houses of worship from the most primitive to the most modern."[11] Every society since those on Malta and at Stonehenge has constructed temples. The construction of these temples lead to the development of the basic principles of building delivery. The development of the arch, the vault and the dome in Mesopotamia six thousand years ago can all be traced to religious structures.[12] But just as important, the initial organization of the building industry itself can be closely tied to these religious structures. As technologies advanced and grew in complexity the Master Builder was born, first to advise the owner (the church or the state) on construction and later to design and build the structures for the owner.

With simple technologies, the consumer of the structure could manage the efforts of the tradesmen himself. The Master Builder concept can be traced from the delivery of complex (typically religious) structures in the early societies of Mesopotamia, Egypt, Greece and Rome and persisted through the construction of the great Gothic Cathedrals.[13] The Master Builder was a craftsmen, versed in the technologies and

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[11]Raskin, page 37.

[12]Hunt, William Dudley, Encyclopedia of American Architecture, (New York, NY: McGraw-Hill, 1980), pages 10, 142 and 543.

[13]Hunt, page 110.

methods of all the building trades, particularly masonry. Due to the length of many large projects, it was not unusual for several generations of a family to serve as the Master Builder for a single structure.[14]

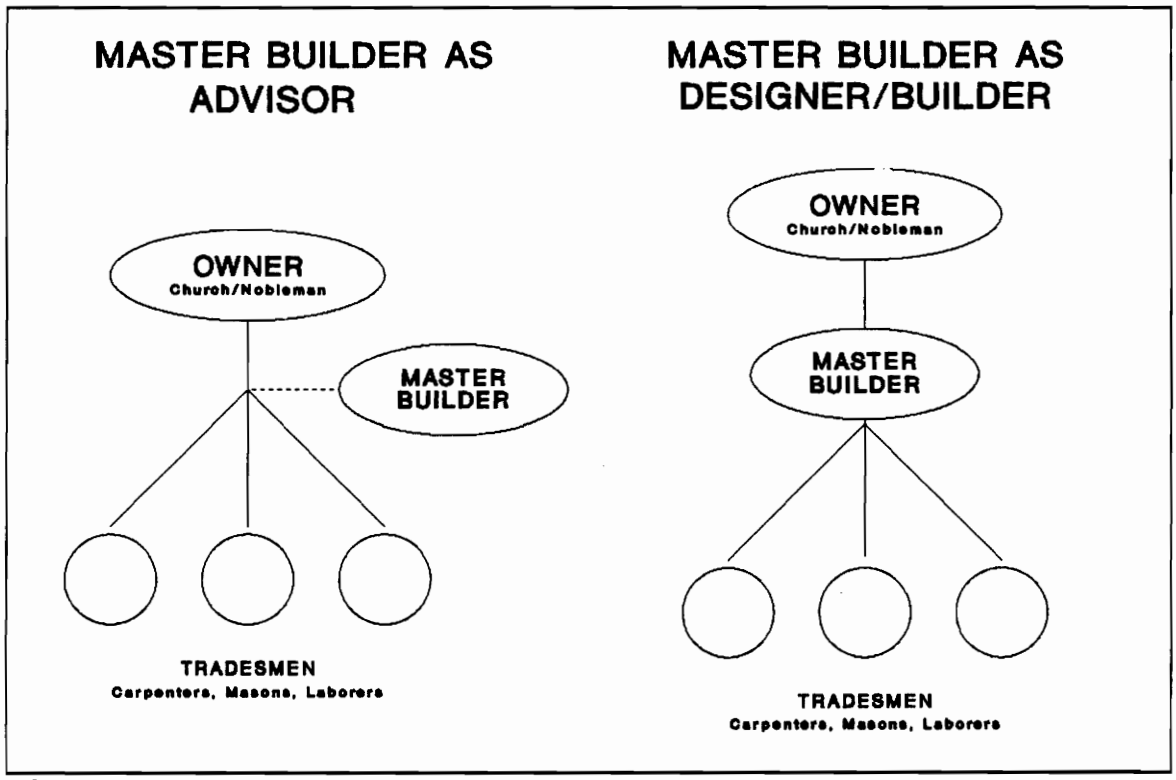

Figure 2: THE MASTER BUILDER

Initially, the Master Builder was a skilled master craftsman utilized by the owner for technical advise and review of craftsmanship (Figure 2). Under this organization, all tradesmen, including the Master Builder were employed by or indentured to the owner. As technology advanced and

[14]Kostof, page 300 - 301

structures grew more complicated, the Master Builder replaced the owner as both designer and supervisor of the work. Craftsmen would be employed by or indentured to the Master Builder rather than the owner. The feudal progression from apprentice to craftsman to Master Builder would continue for centuries. With increased complexity in building technology and an increasing educational system, the Master Builder evolved into the professional Architect.

The architect could be distinguished from the Master Builder in terms of education, status and an increasing role as designer with a decreasing role in the production of buildings. This development is culminating in the *Laissez-faire* design professionals of today and can be traced through the Craftsmen and Gentlemen Architects developed through the Industrial Revolution.

2.3 CRAFTSMAN AND GENTLEMEN ARCHITECTS

By the seventeenth century, the increasing role of the Master Builder as designer lead to the development of both the Craftsman-Architect and the Gentleman-Architect.[15] Figure 3 compares the roles of each of these early professional architects in the construction process. Craftsmen Architects

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[15]Hunt, page 57.

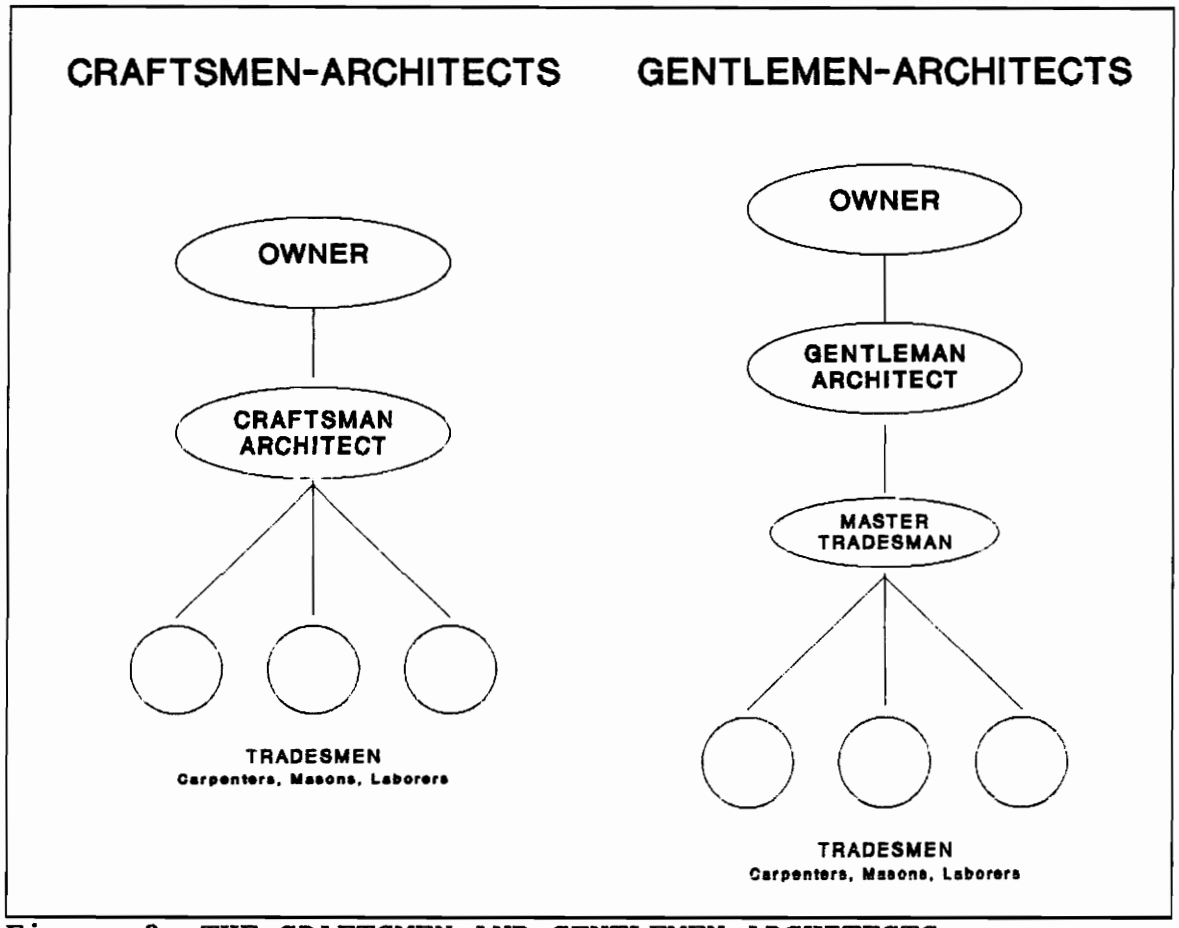

Figure 3: THE CRAFTSMEN AND GENTLEMEN ARCHITECTS

and Gentlemen Architects were both educated in the history of architectural style, design and building technology. By contrast, Craftsmen-Architects were more practically educated while Gentlemen-Architects were more scholastic. In terms of American history, no man epitomizes the concept of the Gentlemen-Architect more then Thomas Jefferson; the well educated "Renaissance Man" of his era studied and "dabbled" in many of the arts and sciences, including architecture.

The Craftsmen-Architects were the Master builders of

their day and were themselves master tradesmen (carpenters and masons) who learned design primarily from practical experience as well as from studying books. The Gentlemen-Architects were amateur designers who learned from the study of classical architecture rather than practical building experience. Both of these designers served the owner directly in delivering the building, with the Craftsman-Architect designing and supervising construction and the Gentlemen-Architect working through a master tradesman for construction. The basic relationship of these designers to the construction industry would remain into the twentieth century, when education, professional recognition and technical advances would again modify the industry's organization.

2.4 *LAISSEZ-FAIRE* ARCHITECT

The construction industry of the twentieth century has undergone several dramatic modifications. Professional recognition, technical advances and legal liabilities have each played a part in the changes to the industry. In the early part of this century, the architect was responsible for both design and construction supervision. As technology became more complex, other schooled professional were relied on to insure accuracy of design, and the architect distanced

himself/herself from the responsibility for the supervision of construction. This isolated designer of today is becoming so distant from the responsibilities and liabilities for the production of the project that he/she could be called the *Laissez-faire* Architect (Figure 4).

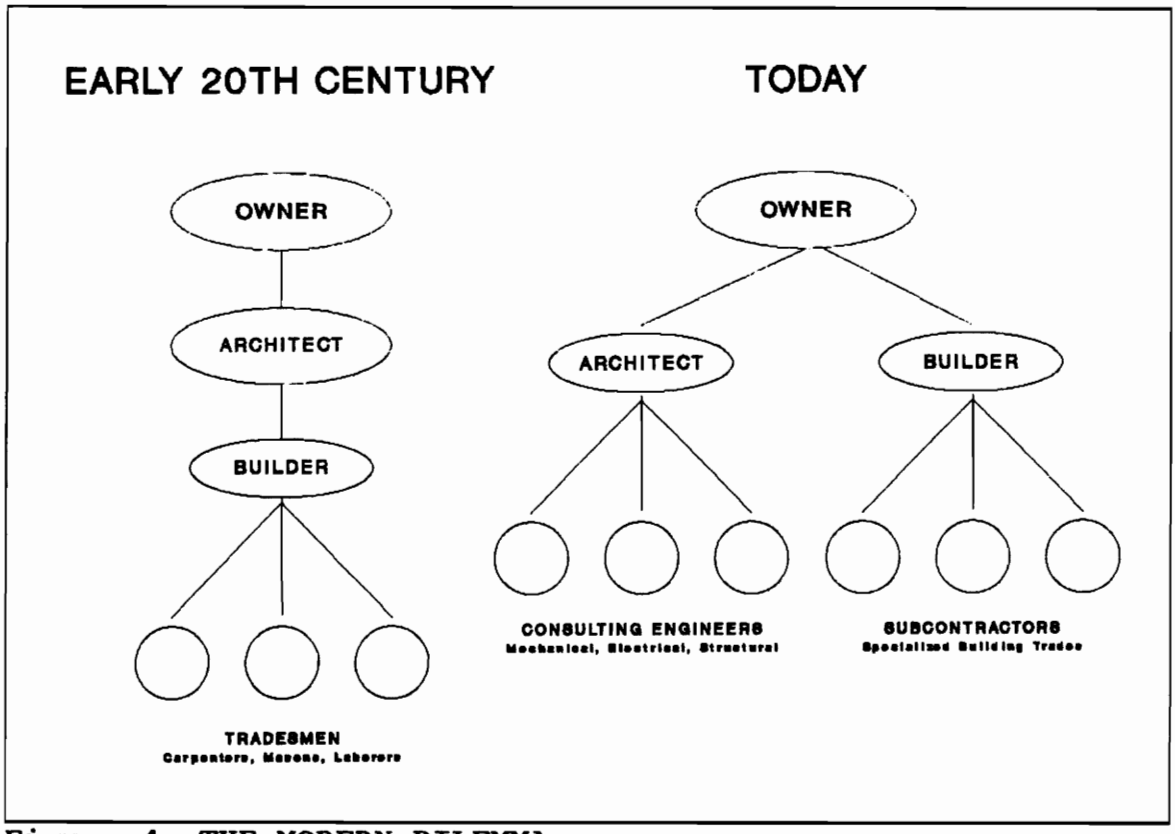

Figure 4: THE MODERN DILEMMA

2.4.1 Development

By the middle of the eighteenth century, the roles of the designer and the builder were being well established and developed. Designers were becoming more educated and less schooled in practical tradesmanship. The separation of the

design and build functions was accelerated in the nineteenth century with the technological advances of industrialization. The designer, the engineer and the builder would now have specified roles within the delivery of building systems. By the beginning of the twentieth century, most of today's elements and relationships within the building industry were in place.[16]

The roles, responsibilities and interrelationships of the construction industry's many disciplines have developed and been modified during this century. This century has seen the architect go from total design and construction responsibility to an increasing isolation. This divergence can be traced as much to professional and liability concerns as to rapid technological advance. The construction organizations of today are significantly varied, but generally reflect the separation of functions illustrated in Figure 4. Alternative approaches to building delivery will be addressed in Section 2.5.

2.4.2 Professionalism

As the knowledge, skills and educational level of the construction designers (architects and engineers) advanced over the past two centuries, so did their status as professionals within society. The professional earns the

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[16]Hunt, page 58.

respect and trust of society because of technical abilities.[17] Professionals are held to a higher standard of care in the preparation for or execution of their duties to the public, and in terms of legal liability "generally held responsible for a professionally correct, safe and timely product."[18]

To determine the "professionally correct" standard of practice and enhance the professional status of the design professions, professional organizations were formed in the middle nineteenth century. With the organization of the American Society of Civil Engineers (ASCE) in 1852 and the American Institute of Architects (AIA) in 1857, standards of practice, educational requirements and professional responsibilities were developed for the professional engineer and architect by the late nineteenth century.[19] In their history, these organizations and others similar to them have enhanced the professional standing of the engineer and architect through development of educational requirements, governmentally controlled registration and internal professional codes of ethics for practice in order to assure and "hold paramount the safety, health and welfare of the

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[17]ELIA, page 761.

[18]Bockrath, Joseph T, Contracts, Specification and Law for Engineers, (New York, NY: McGraw-Hill, 1986), page 332.

[19]Hunt, page 58.

public."[20]

Through registration and licensing, the design professions were able to set minimum educational and experience standards before an individual could serve the public interest. This recognition by state licensing authority helped to elevate the professional status of the design industry. Through growing reliance on educational standards, the registered professional is being distanced from practical production experience. This has resulted in a growing gap between design and production professional.

As the technology base of the industry has grown, architects, engineers and contractors find themselves relying on the assistance and services of consultants and specialized constructors. Consultants have a specialized knowledge in the ever more complex areas of design and production (structural, electrical, mechanical etc). Consultants are used to augment in-house manpower or lack of technical expertise an large, non-repetitive project.[21] As the technical knowledge requirements of these areas grow more complex, no single design or production professional can adequately grasp the

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[20]American Society of Civil Engineers, Code of Ethics, (New York, NY: ASCE, 1977), page 1.

[21]Tufte, Erling, "Effective use of Consulting Engineers", Journal of Professional Issues, Volume 114, Number 2, (New York, NY: ASCE, April 1988), page 163.

intricate details of each aspect of the project.

2.4.2 Liability

As the status of the professions advanced; so did the controls on project execution, both internal and external, to the professional societies. The societies (AIA, ASCE, National Society of Professional Engineers (NSPE) and the Associated General Contractors of America (AGC)) began printing recommended "General Conditions" for both professional services and general construction contracts.[11] These documents specified roles, duties and responsibilities between disciplines and trades. With time and an increasing environment of legal liability, these documents became less general and more specifically shields from responsibility through vague exclusionary clauses, transfers of duties and disclaimers of liability. The most recent edition of the AIA General Conditions for the Constructed Product significantly limits both the architect's roles and responsibilities in the delivery of the building product.

The hazards of the current disjointed approach to the constructed system was tragically illustrated with the 1981 collapse of two suspended walkways at the Kansas City Hyatt Regency Hotel. Following the collapse, which claimed 114

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[11]Pierce, Jotham D and Lyn R Oliensis, Construction Contracts, (New York, NY: Practising Law Institute, 1982), page 311-313.

lives, the city of Kansas City and the National Bureau of Standards conducted extensive investigations into the cause and responsibility for the collapse. The ultimate findings was that the collapse occurred because of an improper design and the incorrect installation of the supporting box-beam connections and supporting suspension rods.[11]

The basis for the improper design and incorrect installation can be traced to a complex organization of firms, sub-contractors and consultants independently responsible for different aspects of the project. This organization, not untypical within the construction industry today, resulted in poor communications and the isolation of the designers from contact with the execution of the project.[14] This isolation lead to inadequate inspection, review and control of the production phase of the project.[15]

The responses to the collapse have been mixed between the elements of the industry. There has been an increase throughout the construction industry in the use of and

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[11]Marshall, R D, E O Pfrang, E V Leyendecker, K A Woodward, R F Reed, M B Kasen and T R Shives, Investigation of the Kansas City Hyatt Regency Walkways Collapse, (Washington, DC: National Bureau of Standards, 1982), page iii.

[14]Hein, Roger A and Yvan J Beliveau, Engineer Professional Liability - The Hyatt Walkway Collapse, Blacksburg, VA: 1990), pages 21-23.

[15]Hein and Beliveau, page 53.

reliability on disclaimers of responsibility both on professional stamps and in contract clauses.[16] The AIA and ASCE both attempted to protect its membership from liability. The AIA by the vague contractual documents mentioned above; and the ASCE through an attempt to enumerate responsibilities by means of a Manual for Professional Practice. These after-the-fact responses to liability protection have advance the isolation of the designer from the production of the building system. The isolation of the designer from construction activities as spurred the development of several alternative approaches to the delivery of building systems.

2.5 ALTERNATIVE APPROACHES

The construction industry has recognized a need for a revised approach to building production. Over the last half century, as the architect has been distanced from the production cycle, alternative approaches to the delivery of structure have begun to emerge. The developments of the professional construction manager and the design-construct contractor have attempted to reduce the impacts of the *Laissez-faire* architect and to provide consumers with complete and responsive services. The general organizations of these

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[16]Hein and Beliveau, page 59.

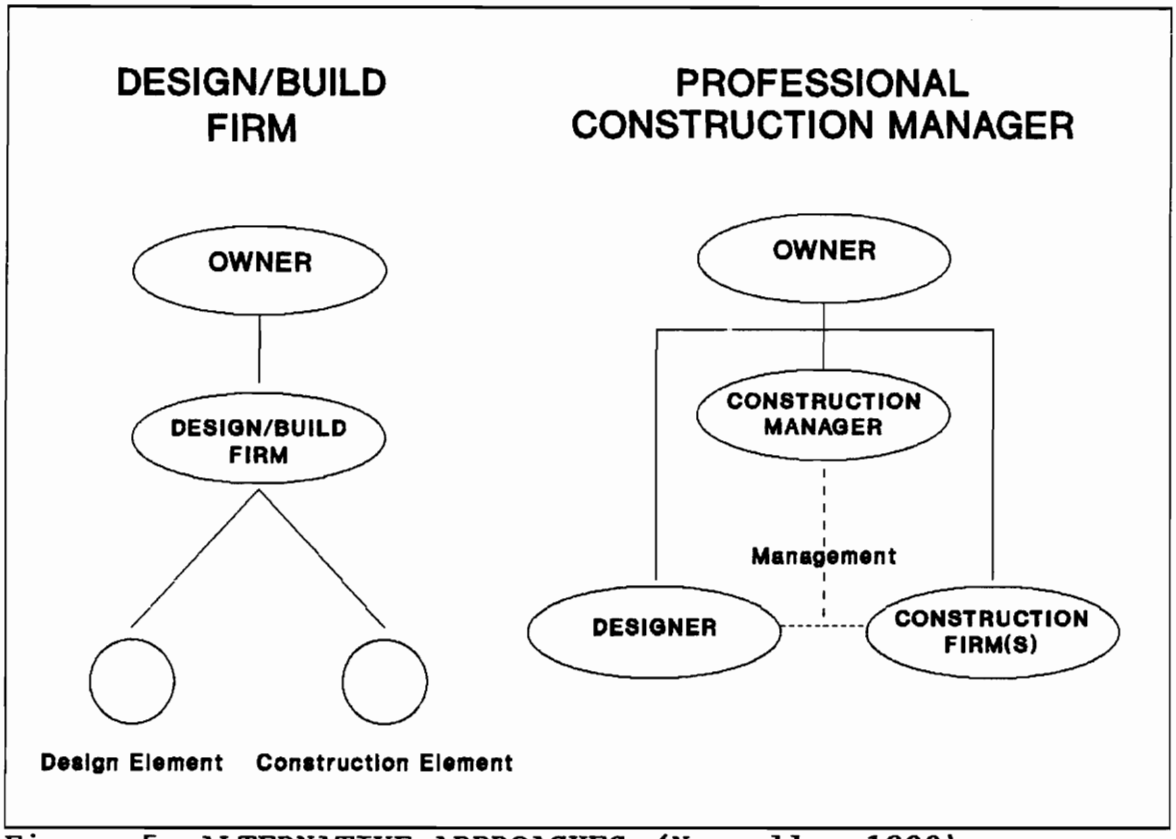

Figure 5: ALTERNATIVE APPROACHES *(Nunnally, 1980)*

two approaches of building system delivery are illustrated in Figure 5[11], but other examples may vary between specific contracts.

2.5.1 Design-Construct

Growing in acceptance and usage today is the *Design-Construct or Design-Build* contracting strategy. The Design-Construct contract integrates the design and production phases of the life-cycle under a single responsible organization, easing communications hurdles between the designers and the

[11]Nunnally, pages 6-7.

builders. "A key aspect of Design-Construct is the team concept. The owner and the designer-builder work closely together in the planning, design, cost control, scheduling, site investigation, and possibly even land acquisition and project financing."[11] The design-construct contractor serves the role of master builder and craftsman architect of the past. This approach, also known as turnkey construction, translates performance-oriented requirements to a final product; in house communication allows construction to be accelerated and often begins before design is complete (fast-tracking).[11]

2.5.2 Construction Manager

Another means of avoiding the hazards of the complex construction industry in use today is to utilize a *Professional Construction Manager* in the delivery of a building system. Under this concept, the construction manager uses his/her knowledge of design and construction to act as the owner's advisor for execution of the project, similar to the original Master Builder. As the owner's agent, the construction manager supervises and manages both design and construction efforts. This approach adds yet another link in the already complex communication network. With three

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[11]Clough, page 16.

[11]Nunnally, pages 5-6.

separate contracts with the owner, and only a management relationship between the construction manager and the design and construction firms; the construction manager assumes very limited financial responsibility for the product and his/her role and authority is limited to the terms of all the contracts.

2.6 SUMMARY

The development of the construction industry to date has seen the rise and possibly the beginning of the end of the architect as the master of the construction process. The increasing distant between the designer and the producer is creating a void which owners want filled by a single agent to hold responsible for project execution. This distance has increased both the complexity of information transfer as well as complicated the already difficult manner by which the industry manages and controls change. The industry has an opportunity to mold the advance to this organization to the technical opportunities of the time, rather than modification of past systems.

The construction industry of today is marked and molded by increasingly rapid changes in organizational approaches and technology. No single professional could grasp nor control

all the rapid advances in building technology, computer applications or management strategies of the past few decades. When these changes are coupled with the increasingly vicious atmosphere of legal liability and the reliance on professional consultants, it is evident that yet another major organizational modification is approaching.

Poor communication has also been fostered through the manners in which firms are selected for a project. Under competitive bidding, the designer must translate his concept to documents for a multitude of potential constructors, each of which could interpret the documents differently. The reliance of the construction industry on competitive bidding is also creating a very volatile financial environment for construction firms.

III. FINANCIAL STATUS OF THE INDUSTRY

"Business is a good game - lots of competition and a minimum of rules. You keep score with money"
- Nolan Bushnell (Founder of Atari)[10]

The construction industry, aside from being the bellwether industry of the American economy, is significantly different than other industries. In this chapter, the economic challenges facing the construction industry will be explored. The impacts of competitive bidding and cost control will be highlighted. Construction is a highly competitive industry which is greatly dependent upon several independent outside elements which can significantly affect success. These differences place a construction firm at higher risk of failure than a counterpart in almost any other industry. The construction industry is fragmented and highly competitive due to the large number of firms and relative easy access for new firms into the industry.[11] Because of the nature of the construction process, the make-up of the industry and the "risky" cash-flow schemes of projects, construction firms are

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[10]Byrne, page 309.

[11]Kangari, Roozbeh, "Business Failure in the Construction Industry", Journal of Construction Engineering and Management, Volume 114, Number 2, (New York, NY: ASCE, June 1988), page 172.

highly sensitive to economic cycles and are subject to high rates of failure.

The rate of construction firm failures has increased dramatically over the past ten years. Most of these failures are due to problems caused by poor financial management.[11] The success of a construction firm relies on its ability to manage the cash-flow cycle of each project. These cash flows work against success from the start of a project, with a large significant negative cash flow at the beginning of each project and delayed repayment schedules. Without accurate bids and proper financial management, a construction firm is highly susceptible to failure. According to Dun and Bradstreet (Figure 6)[11], the most significant cause of business failures in America is economic factors, responsible for 59.7% of overall business failures.

These economic factors are made up of bad profits, high interest rates, loss of market, no customer spending and no future. Of these economic factors, bad profits represents 74.2% of all business failures. The other causes of business failures were related to: the firm's experience (18.2%), sales (11.2%), expenses (6.2%), customer problems (1.3%), fraud and neglect (1.9%), limited assets and capital (1.2%) and natural

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[11]Kangari, page 186.

[11]Kangari, page 173.

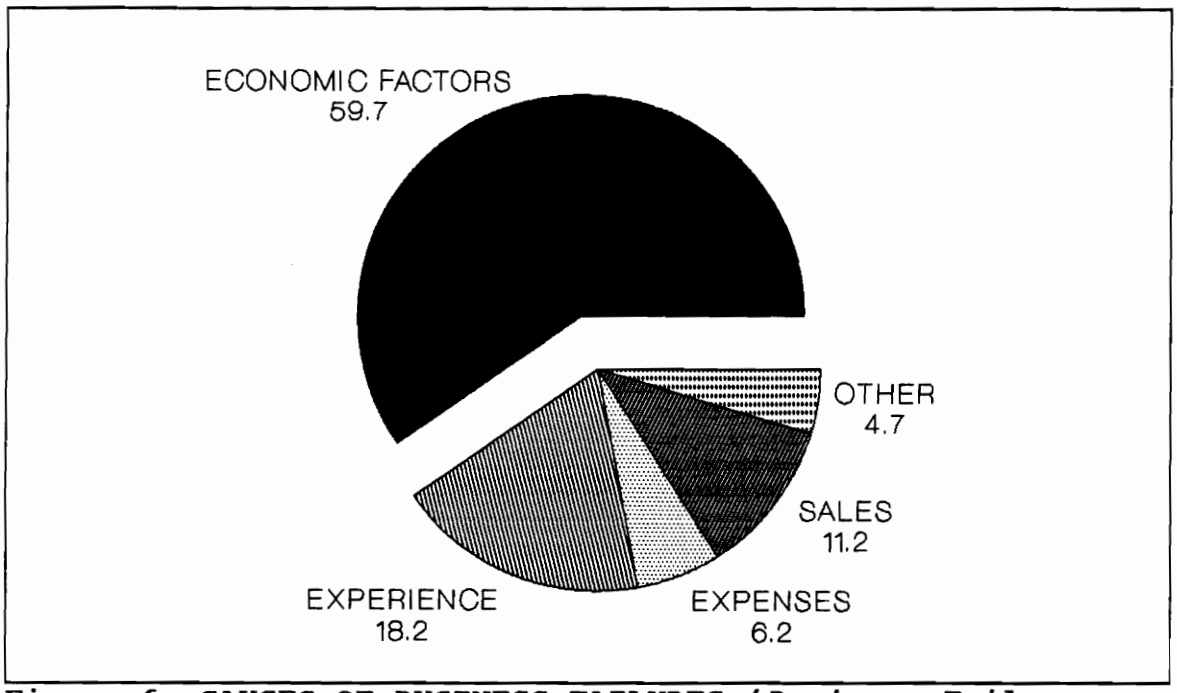

Figure 6: CAUSES OF BUSINESS FAILURES (*Business Failure Record, 1986*)

disasters (0.3%).[11] These proportions clearly illustrate that the cash-flow management of a firm can significantly affects its potential for success or failure.

Based on the nature of the industry and failure evidence, Dun and Bradstreet refined the major causes of construction firm failures as bad profits, management incompetence/lack of experience, inadequate sales, loss of market/economic decline and difficulty in collecting from clients.[12] These findings illustrate a significant need for financial and managerial

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[11]Kangari, page 173.

[12]Kangari, page 174.

tools within the construction industry; specifically, a means to stringently manage and control a project's cash-flows and profit. Unfortunately, the competitive bidding environment significantly restricts profitable pricing practices.

The threat of construction firm failure was heightened with the expansion of competitive bidding within the industry. Although competitive bidding maintains low prices and strengthens competition, it has had a significantly negative effect on the profitability and survival rate of construction firms over the last half century. In the twenty year period from 1950 to 1970, while the value of new construction projects grew by ninety percent, the pre-tax profits of the construction firms declined by ten percent. This disparity can be traced partially to an increase in the number of construction firms, but the primary cause is a movement by contractors towards high volume as a means to assure financial success.[16] However, this increase in volume may be a two-headed dragon. In the competitive bidding environment, the move towards increased volume also causes a reduction in the ability to control prices, reducing them even further.

A construction firm's possibility of failure and profit

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[16]Farid, Foad and L T Boyer, "Fair and Reasonable Markup (FaRM) Pricing Model", Journal of Construction Engineering and Management, Volume 111, Number 4, (New York, NY: ASCE, December 1985), page 374.

are directly related to its control of costs, prices, investments and volume.[17] Because of the nature of the industry, many of these factors are removed from the contractor's control. Competitive bidding practices and the high number of competitors reduces volume potential and can restrict pricing flexibility. Supplier costs, outside investments and client project initiation are outside the contractor's control. Cash-flow control and management remains the only viable means available for a firm to produce feasible pricing and financial management strategies. Unfortunately, "contractors lack of financial and managerial skills coupled with the intense competition inherent in competitive bidding often results in improper pricing decisions."[18] The lack of functional financial and managerial tools have required the contractor to rely on flat-line or market driven profit margins which typically do not include all of the "hidden" costs of a project.

To alleviate the construction firm operator's lack of financial and management skills, several tools have been developed to assist in design, scheduling, estimating and project control. These tools are used in different ways by various members of the building delivery team. Tools

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[17]Farid and Boyer, page 374.

[18]Farid and Boyer, page 374.

available to the modern construction practitioner are not limited to just financial management. Scheduling, design and control tools have significantly advanced with the developments in the computer technology. As with any tools, they are only valuable when properly used, and are only as good as the information given them.

IV. TOOLS OF THE TRADE – 1990

"Men have become the tool of their tools"
– Henry David Thoreau[11]

The increasing complexity of the building system means the construction practitioner can no longer readily understand or control all aspects of a project individually. Tools are continually being developed to facilitate a project's design, planning and control. These tools, many of which exploit the expanding computer technology of today, encompass many aspects of the delivery of a building. Computer application tools which assist in the design and scheduling projects are growing in acceptance within the construction industry. New computer-based applications are being continually being developed to assist in the management, delivery and control of the construction process.[11] The interest, scope and complexity of these tools both in terms of computer and manual applications have significantly advanced in the last twenty years. This chapter will highlight the rapid developments in construction management, design and control techniques which coincide with

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[11]Byrne, page 352.

[11]Beliveau, Yvan J, "CAD Data as the Basis for Project Control in Construction", Civil Engineering in the 21st Century, (San Francisco, CA: ASCE: 1987), page 440.

the competitive bidding explosion and the rapid advances of computer technology.

4.1 NETWORK SCHEDULING

The development of the current network scheduling concept can be traced back to the bar chart approach to scheduling activities developed by Gantt in the first world war's military industry.[11] The bar chart approaches graphically portrays the plan, schedule and progress of a project together. Gantt style bar charts were ineffective in showing the critical interdependence and logic linking activities. As a result of this major discrepancy, in the mid-fifties project planners were in need of a new tools was required to (1) facilitate simultaneous planning and scheduling construction activities, (2) show sufficient detail in dependency relationships to allow for detection of scheduling errors, (3) easily determine progress delays in individual activities, and (4) efficiently set-up, modify and maintain schedules for large construction projects.[12]

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[11]Moder, Joseph T, Cecil R Phillips and Edward W Davis, Project Management with CPM, PERT and Precedence Diagraming, Third Edition, (New York, NY: Van Nostrand Reinhold, 1983), page 5.

[12]Skolnick, Jeffrey F, Visual Schedule Simulation System, (Blacksburg, VA: VPI&SU, 1990), page 16-17.

The development of network based planning methods in the late fifties allowed planners to incorporate project events' interrelationship as well as there time sequence into the project schedule. The development and application of network planning, specifically CPM (Critical Path Method) and PERT (Program Evaluation Research Task) grew rapidly in the sixties and seventies. Network scheduling and planning evolved from a simple scheduling tool to a means to allocate and balance resources over a project's life-cycle.[41] The efforts of the late seventies were to fix cost of resources used to the network analysis of their scheduling.[42] The result was an accurate picture of a project's fixed cash-flows and therefore its estimated cost.

As the complexity and expense of building systems advanced, the industry recognized the need to advance the management of cash-flows within the construction project. In the middle 1970s a movement began to link a project's cash-flow management to its network scheduling and planning tool. Using standard cost estimates for resources (materials, manpower and equipment), these resources and cost were applied

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[41]Moder, Phillips and Davis, pages 3-8.

[42]Reinschmidt, Kenneth F and Walter E Frank, "Construction Cash-flow Management System", Journal of the Construction Division, Volume 102, Number CO4, (New York, NY: ASCE, December 1976), pages 616-619.

to activities to develop an accurate picture of project costs over the project schedule. This approach recognized the time sensitivity of capital expenditures for major construction projects in the volatile economy of the time.[45]

As the personal computer industry evolved, computerized scheduling tools employing the principles of CPM and PERT moved from large mainframe computers to less expensive personal computer applications. Computer technology offers several advantages to network planning: (1) plan and schedule data can be rapidly manipulated, sorted and output by various parameter (float, early/late start dates, responsibility codes, resources requirements) to help simplify management tasks; (2) once stored, the network can be easily updated to illustrate progress or changes in estimates throughout the project's life-cycle; and, (3) certain analysis that go beyond schedule calculations are only practical with computer assistance (time-cost tradeoffs, resource allocation/leveling and cost control).[46]

4.2 COST MODELS

With the allocation of resources over the schedule of

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[45]Reinschmidt and Frank, pages 615-616.

[46]Moder, Phillips and Davis, page 338.

the project, a time sequencing of the fixed cash-flows could be developed. The price of the project would no longer be viewed as a lump-sum, but could be accurately viewed as a series of time and activity dependent expenditures. These expenditures are rarely equally incurred in the life-cycle of a project. Knowledge and understanding of this non-linear cash-flow pattern is vital for effective financial management.

The combination of network scheduling with the resource costs develops a clear picture of the dynamic cash-flow structures of a project. When linked with the known contractual delays and reductions of payments, an accurate picture of a project's timed cash-flows can be developed. "The inclusion of interest charges, variable escalation rates and non-uniform expenditures permits the investigation of some realistic aspects of the financial planning problem in construction projects."[47] This combination of fixed cash-flows can be developed to reveal the required investment for the project and can be used to illustrate the effects of economic factors on the cash-flows. The development of these time sensitive realistic views of cash-flows enabled future developments in the simulation of pricing strategies in the construction industry.

The development of an accurate bid price for a

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[47]Reinschmidt and Frank, page 627.

construction project has long been viewed as the cornerstone of effective financial management. The oldest negotiating tool available for the development of an effective bid was the contractor's knowledge. A contractor who understands the market economy and the available and true costs of labor and materials has a better position from which to bid a project.[46]

The successful construction price in a competitive bidding environment is a paradox; it must be high enough to assure a profit, but low enough to be chosen. "But the only way to be sure of having the low bid is to bid below cost."[47] The competitive bid faces the contractor with two disastrous outcomes: "(1) an excellent chance of making no profit with a low bid, or (2) no chance at all of making a profit with a high bid."[48]

The industry has attempted to develop tools for the contractor's preparation of bid prices which get the job and assure a reasonable profit. These tools can be divided into two basic groups. The first group are competitive bidding strategies which analyzes competing bidders' history to establish the maximum profit margin which allows a probability

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[46]Gooch, Kenneth O and John Caroline, Construction for Profit, (Reston, VA: Reston Publishing, 1980), page 103.

[47]Park, page 1.

[48]Park, page 1.

of success. The second and more recent development are models which incorporated cash-flows and economic requirements to develop an economically feasible bid.

4.2.1 Competitive Models

Competitive bidding models are based on the probability of success against known competitors. This type of model was originally development in the early seventies through the works of various engineers working separately (Friedman, Gates, Rosenshine and Dixie) which caused significant debate throughout the decade. The models were centered around one general problem:

> "n sealed bids, including my bid B_0 (Bid of Contractor "0"), are to be submitted in competition for a contract. What is the probability the I, C_0 (Contractor "0") will win the contract? (Naturally, it is assumed that the low bid wins)"[51]

These models focused on success in undercutting the competition, rather than determining a bid which was representative of project costs. These models accelerated the competitive bidding dilemma rather than developing a tools to assure success.

4.2.2 Pricing Models

Pricing models are concerned with the economic effects of the cash-flows of a project on the development of a

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[51]Rosenshine, Matthew, "Bidding Models: Resolution of a Controversy", Journal of the Construction Division, Volume 98, Number CO1, (New York, NY: ASCE, March 1972), page 143.

reasonable bid. Pricing models have been explored which consider the affects of economically tumultuous climates on the effective bid price of a project. Based on the work of Foad Farid and L T Boyer, these approaches center on the development of a Fair and Reasonable Mark-up (FaRM) to determine a Minimum Acceptable Price (MAP). The FaRM based models use the projects time sensitive cash-flows, the economic environment and the firm's Required Rate of Return (RRR) to determine its MAP. "FaRM would be viewed as the smallest mark-up which satisfies the Required Rate of Return (RRR) of the contractor for the particular (or at least the general risk-class of) project at hand."[11] Such pricing models incorporate the effects of schedule and basic engineering economy principles to develop a realistic bid which covers costs and yields a minimum required profits. This approach to bid price development, if universally accepted, would break the cycle of the competitive bidding dilemma.

4.3 COMPUTER AIDED DESIGN (CAD)

"Graphical representations of both physical and work activities on projects have been essential tools of the

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[11]Farid and Boyer, page 376.

construction industry for decades."[11] In the past twenty years, the microcomputer has increasingly replaced the expensive and laborious manual methods of producing the interactive graphical representation of the constructed product. Computer Aided Design (CAD) tools have developed to provide the design data base that replaces the volumes of specifications and sheets of drawings which previously represented the project. The ability to store, retrieve, modify and interface this and other data bases makes CAD applications a vital link in the design and control systems of the future.

Simply defined, CAD is the user-oriented use of computer systems to assist in the creation, modification, analysis or optimization of a design in the form of pictures and symbols.[12] CAD applications within the construction industry are a more recent development when compared to there long standing applications in computer aided manufacturing (CAM). CAD interfaces with CAM process have long been accepted as means to translate design information to execution by Numerical

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[11]Hendrickson, Chris and Tung Au, Project Management for Construction, (Englewood Cliffs, NJ: Prentice-Hall, 1989), page 74.

[12]Groover, MP and E W Zimmer, CAD/CAM: Computer-Aided Design and Manufacturing, (Englewood Cliffs, NJ: Prentice-Hall, 1984).

Controlled (NC) machinery.[15] As acceptance of CAD as a primary design tool has increased in architecture and engineering, the exploration of its interface with construction processes to facilitate control has expanded.

Through the use of animation simulators, CAD data can now be manipulated to produce accurate three dimensional representations of designs. The viewer can be "placed" at any location within the design's coordinates to view the elements of the facility at varying degrees of detail. A leader in this application technology is Bechtel Power Company who has developed a animation simulator known as "WALKTHRU".[16]

Accurate and broad based computerized network scheduling tool and CAD provides the basic data bases required for advanced construction control developments. Interactions between the schedule data base, the design data base and the animation simulator facilitates the evaluation of project progress through time-sensitive computer simulations of either design or operation.[17] Because of CAD's abilities to define

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[15]Voelcker, Herbert B, "Modeling in the Design Process", Design and Analysis of Integrated Manufacturing Systems, (Washington, DC: National Academy Press, 1988), page 168-169.

[16]Skolnick, Jeffrey, Ayman A Morad and Yvan J Beliveau, "Development of CAD-based Construction Visual Simulation System", Project Management: Tradition and Transition, (Drexel Hill, PA: PMI, 1990), page 335.

[17]Skolnick, Morad and Beliveau, page 334.

positions in three dimensional terms, other applications involving these interfaces being developed includes the layout and control of resources and production equipment, spacial congestion analysis, information delivery to site personnel and project quality control.[11] This interface ability is leading to the basis for the computer controlled and robotic construction industry of the twenty-first century. The interaction of information could be even more significantly enhanced by coupling it with knowledge-based or "expert" computer systems.

4.4 EXPERT SYSTEMS

To take the maximum advantage of the benefits of the computer revolution, the construction industry is developing not only means to interface the data of CAD and network scheduling applications, but is improving their applications with the incorporation of expert computer systems. Expert systems are a result of researching Artificial Intelligence (AI). "In limited problem domains such as equipment configuration or process control, knowledge based systems have been demonstrated to approach or surpass the performance of

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[11]Beliveau, page 440-441.

human experts."[59]

Expert system and knowledge based system are frame-based or rule-based AI software products "that incorporates a set of rules, the rule base, plus a software system for manipulating the rule base."[60] A rule consists of two parts, the precondition and a postcondition. The precondition represents the conditions, events or situations which must be satisfied in order for the post condition to be true. As a "carnivore", the postcondition can only be true or exist if all aspects of the precondition are present. Knowledge based systems exploit the basic rules-of-thumb of the process to develop the preconditions and their relationship to the postcondition.[61]

The application of expert systems to the construction process will accelerate with the proliferation of computer involvement. An expert scheduling system will recognize that foundation work must precede structural erection; formwork must precede concrete placement; interior walls must be present before surfaces can be finished. Expert systems in design can similarly avoid position conflicts between

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[59]Hendrickson and Au, page 75.

[60]Schach, Stephen R, Software Engineering, (Homewood, Ill: Irwin, 1990), page 445.

[61]Schach, page 445-446.

structural, mechanical and electrical elements.

The use of expert systems to analyze and facilitate the interface of data bases can significantly enhance the construction process. Current time consuming manual checks and reviews and be accurately accomplished by knowledge based computer systems. This process can avoid communications delays and review problems currently experienced in the design process. Expert computer systems will expedite both the design process and the review and checking procedures. This concept of expedited and accurate automated design yields the parametric design concept. In parametric design, functional and other requirements are input into a knowledge-based system which delivers a completed facility design.

The communications problems currently experienced between design disciplines in the review process could be significantly reduced by a knowledge-based interface and communication system between the practitioners. This enhanced interaction of project design, schedule and control data bases can form the basis for a revised approach to construction information management. This knowledge based process would eliminate the costly communications and spacial conflicts which resulted in the modifications to the construction process of the past.

4.5 OBJECT ORIENTED DATA BASES

The management of data is a significant challenge facing the construction industry. Many elements of information manifest themselves within single elements within a design. Object oriented data base enable the contributing characteristics, restrictions or data that developed a particular element or space within the design to be continually linked to that object. As the design process grows increasingly automated, such data bases can be utilized to identify and thus resolve both physical and logical conflicts between objects.

Traced to the SIMULA effort of Dahl and Nygarrd in 1966 and further developed by Xerox in the Smalltalk research project, object oriented data bases integrate the strengths and benefits of traditional data base systems (relational, hierarchical and network).[11] Object oriented data bases treat objects in the same manner a network systems treat activities; linking specific development information to the object in the same manner as networks link resources. All input is treated as a separate object, with each object, either physical or

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[11]Kim, Jae-Jun and C William Ibbs, "ODEPSI: An Experimental Object-Oriented DBMS", Journal of Transportation Engineering, (New York, NY: ASCE, 1990), page 2.

conceptual, uniquely identified by the system.[11]

When combined with knowledge based technology, object oriented data bases can make the parametric design concept practical. Since object oriented data bases link all developmental factors to required objects within the design, decision parameters can be included allowing knowledge based expert systems to perform design decisions, thus leading to parametric design. The design will resolve the conflicts identified within the system rather than generation of alternatives. In order to be fully functional, such a system must incorporate all information sources which determine the configuration or location of objects. The *Total Life-cycle Construction (TLC)* information management concept is envisioned to employ this computer technology with facility life-cycle concepts and facility delivery procedures to develop such a tool.

4.6 SUMMARY

The manner in which the tools available to the modern construction practitioner are managed will determine the shape of the construction industry of tomorrow as much as the organization of the participants in the construction process.

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[11]Kim and Ibbs, pages 2-3.

The development of new tools to control the construction process from design through occupation are piecemeal. They represent the automation of current practices, rather than a systematic revision of the process to improve the organization and execution of the building system.

When viewed as a delivery system, the design and production of a structure significantly contributes to the overall life-cycle of a building. If a structure is viewed as a product, its development, delivery and operation is not that much different then any other complex system. Since the Second World War, a methodology known as Systems Engineering has significantly enhance the process of delivering such complex systems. To develop a revised alternative approach to the construction process, the understanding and application of this methodology is a vital step.

V. THE SYSTEMS ENGINEERING APPROACH

"If a man will begin with certainties, he shall end in doubts; but if he will be content to begin with doubts, he shall end in certainties."
- Francis Bacon[44]

The world is a complex combination and interaction of systems; the construction industry is no exception. In its most basic term, a system is "an assemblage or combination of things or parts forming a complex or unitary whole."[45] Systems are either naturally evolving, "Natural Systems" or the result of human intervention and development, "Man-made Systems." Natural Systems represent the environment occurring around us, the waterway networks, the mountain ranges, the rain forests, the oceans, the deserts and the indigenous life of each. Man-made Systems form the environment which humans have altered, modified or created for their use and benefit.[46]

As technology and humans have advanced, so have the number of systems, complexity of systems and the human's reliance on man-made systems. This explosion of systems has

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[44]ELIA, page BT-67.

[45]ELIA, page 997.

[46]Blanchard, Benjamin S and Wolter J Fabrycky, Systems Engineering and Analysis, (Englewood Cliffs, NJ: Prentice-Hall, 1981), page xi.

resulted in the need for a science of understanding, developing and managing these complex systems. Since the Second World War, these sciences (Cybernetics, General Systems Theory and Systemology) have developed into what is known today as Systems Engineering. In this chapter, the development and application of Systems Engineering principles to the construction industry will be discussed.

5.1 BACKGROUND

The Second World War, among its other impacts on humanity, marked the transition from the *Machine Age* to the *Systems Age*. The Machine Age was the post Industrial Revolution period when machines began to replace man as the source of physical work. "In the Machine Age, understanding the world was taken to be a sum, or resultant, of an understanding of its parts which were conceptualized as independently of each other as was possible."[17] This philosophy also reduced each relationship between independent elements as a singular cause and effect, without further interaction between or among other components.

"Most of the theories and devices developed up to the time of the Second World War were of sufficient simplicity

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[17]Blanchard and Fabrycky, page 14.

that it was possible for a single mind to comprehend them. As an engineer, Henry Ford knew every part in his Model-T; as a manager, he knew every aspect of its mass production."[11] Although a specific date can not be affixed to the beginning of the Systems Age, it could be readily conceived as that point in time when devices became so complex and interrelated that a single mind could not comprehend all facets of the product's design, production and operation.

The science of managing and understanding the complex interrelationships of such extensive systems has clearly advanced since the Second World War. The late 1940s and early 1950s saw many attempts to manage the development and delivery of systems. These attempts can be summarized into three significant approaches and developments within Systems Engineering, Cybernetics, General Systems Theory and Systemology. Cybernetics was a systems design approach which was based on understanding system's self-regulation. The General Systems Theory approached development through understanding system's interrelationships. Systemology developed and used the principles of Operations Research for forward understanding of system interrelationships.

These developments in Systems Engineering theory

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[11]Drew, Donald R and Charng-Horng Hsieh, A Systems View of Development, (Taipei, ROC: Cheng Yang, 1984), page 3.

coincided with the rapid growth of scientific knowledge and an increase in specialization. From the eighteenth through the twentieth century an overspecialization in the scientific and engineering worlds caused a proliferation into over one hundred distinct disciplines.[6] The synthesis and integration of the knowledge and efforts of these approaches and the multitude of scientific and engineering disciplines into a coherent product is the goal of Systems Engineering.

5.2 SYSTEMS ENGINEERING

Systems Engineering is a beast with many heads, and an equal number of definitions. One definition views Systems Engineering as systems analysis activities that employ simulations and optimization to define and refine a complex system's parameters. Another view of Systems Engineering is the management of complex engineering systems stressing interface control, functionality, reliability, support and acquisition.[7] Systems Engineering is all of this and more. In formal terms, Systems Engineering can be defined as the

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[6]Blanchard and Fabrycky, pages 9-13.

[7]Mar, Brian W and Richard N Palmer, "Does Civil Engineering Need Systems Engineering?", Journal of Professional Issues in Engineering, Volume 115, Number 1, (New York, NY: ASCE, January 1989), page 45.

"application of scientific and engineering effort to the life-cycle of a system; stressing the transformation of a need to performance parameters, while integrating technical parameters, functional design factors and multiple engineering disciplines."[71] But probably a more simple definition and the one used for this project and report is "*the integration and evaluation of complex engineering systems or problems to ensure that the final product satisfies the original requirements*".[72]

Regardless of the definition, the Systems Engineering Approach embodies three key elements.[73] First, Systems Engineering views the system in totality; it analyzes not merely independent components but the total system integration over the entire desired life-cycle of the system, from conceptual design through system retirement. Second, Systems Engineering embodies formalized methodologies and techniques for the development, design and analysis of the system. And finally, Systems Engineering approaches tasks with a multi-disciplinary team approach, melding the knowledge and techniques of various engineering disciplines to achieve an optimum solution. This interdisciplinary management improves

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[71]Blanchard and Fabrycky, page 24-25.

[72]Mar and Palmer, page 45.

[73]Drew and Hsieh, pages 8-9.

communication, and minimizes the duplication of effort or the failure to address a problem. The combination of these three elements allows Systems Engineering to expose and thus manage the multitude of problems, disciplinary interactions and communications problems within a complex or extensive system over its entire programmed life-cycle.

5.3 CONSTRUCTION AND SYSTEMS ENGINEERING

The construction industry is probably the most dramatic example of the need to incorporate the principle of Systems Engineering within Civil Engineering. With its increasing complexity and integration professional disciplines and technical trades, the construction industry could benefit from the application of Systems Engineering principles. Each of the construction participants (consumer, architect, engineer and construction tradesman) views a building system through independent and very specialized eyes. The current approaches to project development and execution limit communication and feedback between the various disciplines. This poor communication can be traced as the cause for many of the problems within a project. The hazards of this disjointed approach to the constructed system was tragically illustrated with the 1981 collapse of two suspended walkways at the Kansas

City Hyatt Regency Hotel.

The discipline of Civil Engineering is concerned with the development of large and complex systems which alter or enhance the physical environment. These systems are used by humans for work, living, moving or providing the means to improve life. As technology and the Civil Engineering knowledge base has grown, the field has been fragmented into many specialized subdisciplines (hydraulics, soil mechanics, transportation, geodesy, construction, etc.) "These groups appear to be continually diverging and new specialty fields within Civil Engineering keep emerging. Even the amount of knowledge shared by Civil Engineers seems to be diminishing as the specialty fields continue to fragment."[74] As Civil Engineering and construction projects become more complex, various "specialty groups" will be required to interact, as the ability of one subdiscipline to understand all aspects of the project diminishes.

The benefits of the Systems Engineering approach to managing complex interactions has long been misunderstood or ignored within the profession.[75] Systems Engineering developed within the rapid growth and complexity of the aerospace and defense industries following the Second World War as a means

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[74]Mar and Palmer, page 46.

[75]Mar and Palmer, page 46.

to manage the development and acquisition of complex systems. With the increase in complexity and specialization, the construction industry shares several common concepts with the defense or aerospace types of system development and acquisition. The incorporation of Systems Engineering concepts in building systems will provide "more rigor and discipline and provides much more visibility of the technical decision to the client."[76]

To alleviate poor communications and give the needed exposure to technical decisions, the principles of Systems Engineering can be applied to assist in the delivery of building systems. By viewing the construction project as a interdependent system rather than a none integrated series of technical actions, the applied principle of System Engineering can help to alleviate communication problems and develop tools to assist in smooth execution.

5.4 THE LIFE-CYCLE APPROACH

The cornerstone of the Systems Engineering approach is the holistic view of the problem over the entire intended functional life of the system, "from cradle to grave". Figure 7 illustrates the interaction of the life-cycle phases and

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[76]Mar and Palmer, page 46.

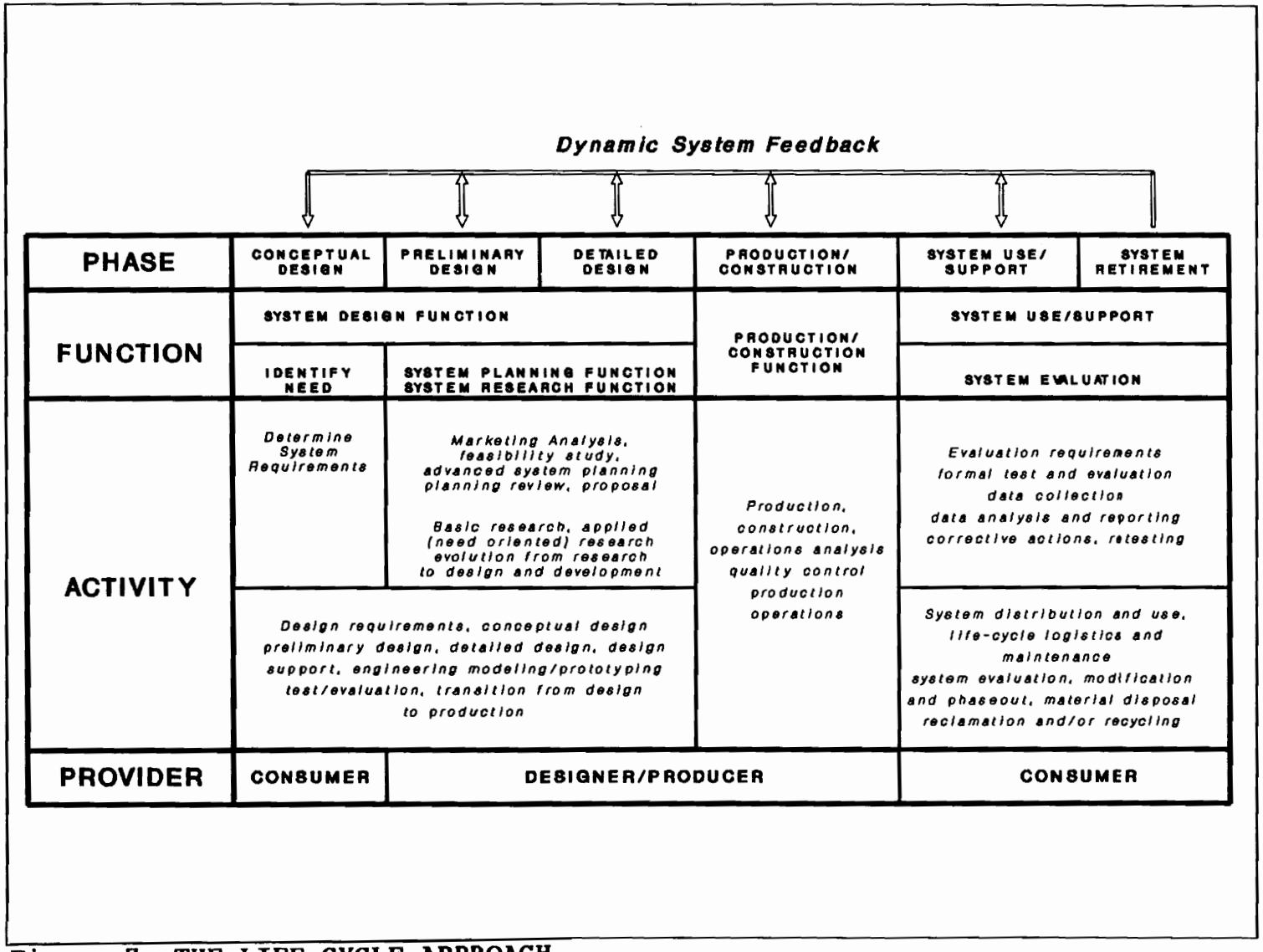

Figure 7: THE LIFE-CYCLE APPROACH

provides examples of functions and activities included in each phase. The system is viewed as the integration (rather than separation) of disciplines, elements, knowledge and techniques over the entire life-cycle of the problem, project or system. "The life-cycle of a system or product begins with the initial identification of a need and extends through planning, research, design, production or construction, evaluation, consumer use, field support and ultimate product phaseout."[11] The conceptualization of the system over its life-cycle and across disciplinary lines can expose many "hidden" elements and costs within the system.

The key aspect of the system life-cycle approach is feedback, not only between participants, but also between phases. Dynamic feedback enables the reduction of interdisciplinary communications problems and enables the systems engineering approach to respond to and incorporate modifications and changes rapidly into the system's design process. Feedback represents the interdependent nature of the building system, a minor modification by one participant in an early phase of development can significantly hamper functions or operation in later phases. Proper decisions based on feedback early in the project's life-cycle also saves time and money; the later the change or modification occurs

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[11]Blanchard and Fabrycky, page 19.

in time, the more costly and difficult it is to execute. Figure 8[11] illustrates the relationship of decision time to percent of project cost reduction opportunity and cost commitment. The construction industry provides an illustration of the dangers of this. The industry's reliance on "Change Orders" and claims for additional work, time extensions and money to correct design errors significantly increases costs and delays projects. The root cause of these problems is the poor communication of project requirements between participants in the process. Because of the complexity of the process in construction, the participants have a decidedly limited ability to adapt to change.

The dangers of inability to respond to and incorporate change can also be demonstrated in the demise of the nuclear power industry. It can be argued that the "death" of nuclear power plants was not due to environmental or cost considerations, but to the facilities' design-construct system to keep pace with increasing regulatory changes. Had a better system of implementing change been available the issues of regulatory changes and environmental and economic pressures could have been handled and the process continued. As a project advances from a static change environment (simple,

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[11]Fabrycky, Wolter J and Benjamin S Blanchard, Life-cycle Cost and Economic Analysis, (Englewood Cliffs, NJ: Prentice-Hall, 1990), page 1.16.

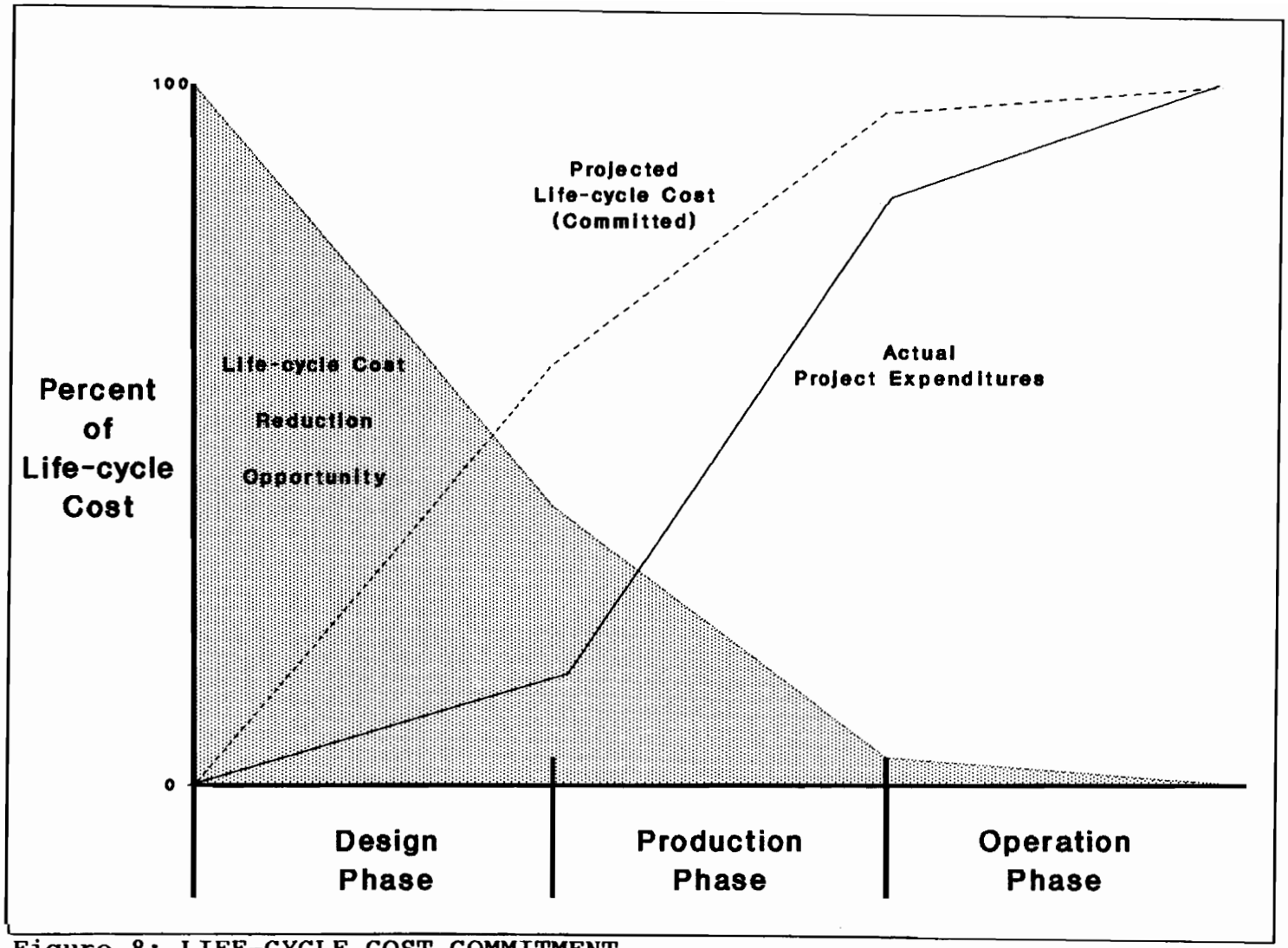

Figure 8: LIFE-CYCLE COST COMMITMENT
(Adapted from *Fabrycky and Blanchard, 1990*)

small scale or repetitive systems) to a more dynamic project (complex, large scale individual systems) the required ability to manage change increases (Figure 9). It is this ability to feedback information and respond to change that the Systems Engineering approach fosters which can be beneficially applied to the construction industry.

5.5 SYSTEM ENGINEERING TOOLS

Systems Engineering uses many tools to facilitate the integration of the elements of a system. These tools have often been developed in different disciplines for different purposes, but their combined application can predict and enhance design, production and operation of a system. The basic premise is modeling the system. The manipulation of models through simulation can represent critical aspects of the system and provide significant timely information for the analysis and modification of the system.[11]

The functional analysis of the system model using the principles of engineering economics, human factors, optimization, reliability and other fields provides the framework for the system's development. The functional flow of the system is divided into discrete interrelated functional

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[11]Blanchard and Fabrycky, pages 42-52.

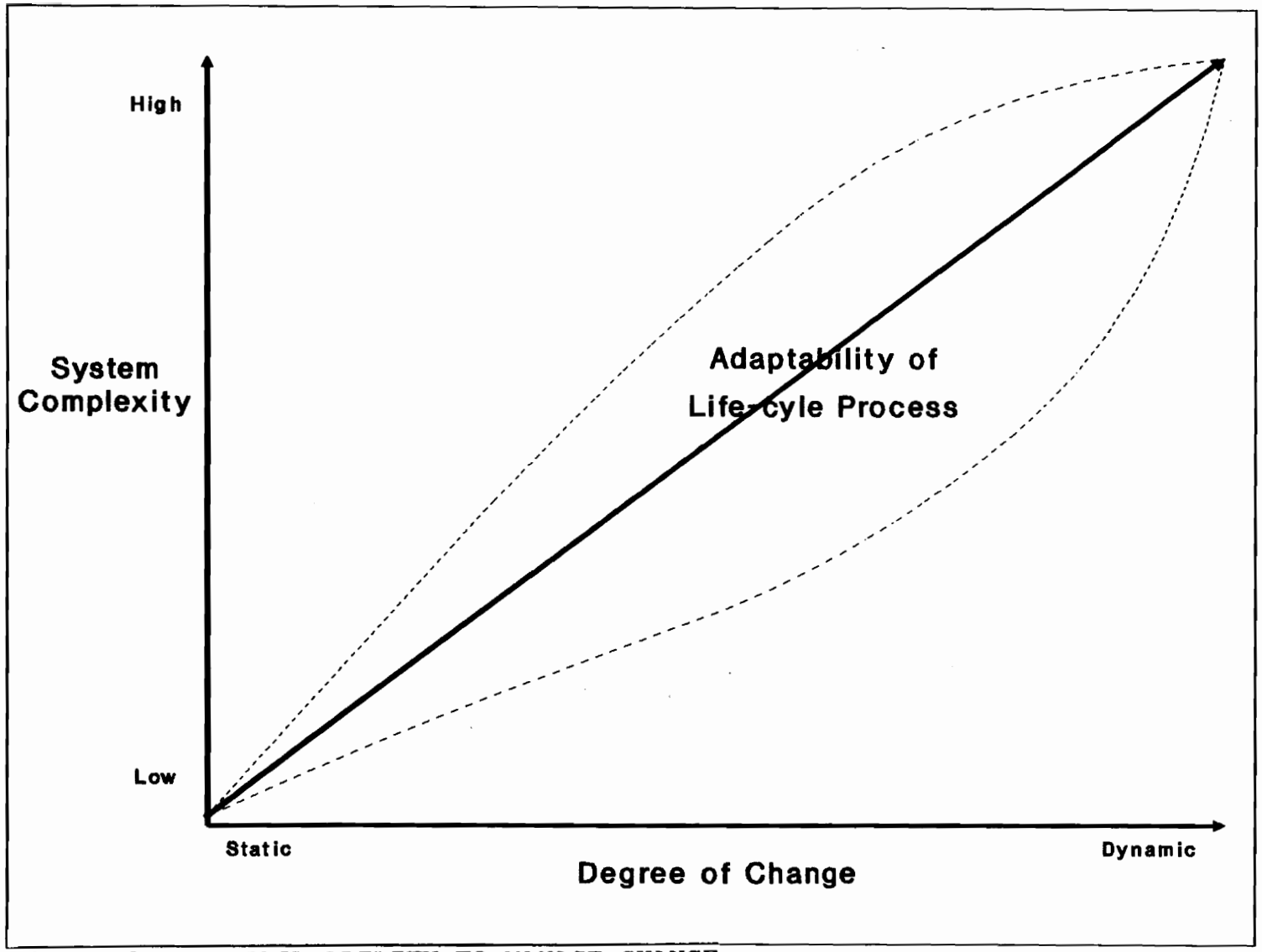

Figure 9: REQUIRED ABILITY TO MANAGE CHANGE

and operational requirements. These interrelated elements are organized and linked over the planned the life-cycle of the system. This process then results in a model of functional interactions and requirements which form an accurate representation of the system. The model can then be analyzed and modified by feedback requirements to simulate the complete "cradle to grave" (design, production, operation and retirement) requirements of the system or facility. This process highlights the necessary relationships and the critical dependency of processes and elements within the system's development."

5.5.1 Systems Dynamics

Systems Dynamics is a systems management and modeling technique which views systems and organizations from a control system perspective. The systems dynamics is an approach which models a system's operation, structure and policies to determine how interaction influences the success or failure of the project, system or facility."

System dynamics analyzes a system under two important considerations: time and feedback. Each of these elements significantly affects a system's state. The system's state at a particular moment in time represents the status, value

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"Blanchard and Fabrycky, pages 256-258.

"Drew and Hsieh, page 388.

or nature of system attributes at a particular moment in time. The system status is both a quantitative and subjective "snap-shot" of the system, and can be used to evaluate the impacts of future developments or changes on the system. Dynamic system feedback represents the interactive nature of the elements which compose the system; reflecting the fact that a change in one aspect will alter other components and the overall system. Application of changing inputs or policies will alter the state of the system over time.

Through the applications of the techniques of systems dynamics (causal diagrams, system equations development and integration), a model of the complex interaction affecting a system can be developed. The operation of the model of time can then be simulated and predictions of performance made. Adjustments to the model input can easily be made to facilitate the analysis of the effects of various courses of action on a system.

5.5.2 Logistics Engineering

The concepts of logistics engineering highlights one often overlooked aspect of the building system: the support and requirements of the product after delivery during the operational phase of the life-cycle. The design and production of the building system rarely incorporates all elements of the operational and maintenance requirements of

the structure in its design. "Logistic support is viewed as the composite of all considerations necessary to assure effective and economical support of a system throughout its programmed life-cycle."[11]

Considerations of maintenance and support must be considered in all phases of the life-cycle. Just as constructability feedback is required in the design phase to facilitate production; concepts of access, repair and replacement of components as well as their operational costs (fuel and utilities costs) must also be considered in design. Failure to consider these elements can increase operational costs of the structure. Logistics considerations are not confined to merely the operation of the facility, but includes the materials, manpower and equipment required for the production (or construction) of the facility. As illustrated previously, early exposure of these elements will allow trade-off analysis of options to reduce turmoil and life-cycle costs. The goal of logistics engineering is the timely and economical support of the system throughout its entire life-cycle. Component reliability, the system maintenance concept and plan, as well as the provisioning of replacement components and sustainment materials are all elements of

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[11]Blanchard, Benjamin S, Logistics Engineering and Management, third edition, (Englewood Cliffs, NJ: Prentice-Hall, 1986), page 9.

logistics engineering.

To facilitate the analysis, systems engineering utilizes *Logistics Support Analysis (LSA)*. LSA is an iterative process to determine and evaluate logistics support requirements of the system continually throughout the system's life-cycle. "LSA constitutes the application of selected quantitative methods to (1) aid in initial determination and establishment of logistics criteria as an input to system design, (2) aid in the evaluation of various design alternatives, (3) aid in the identification and provisioning of logistics support elements, and (4) aid in the final assessment of the system support capability during consumer use."[11] The benefits of the LSA to the design are two-fold; first, it identifies support requirements, and secondly, it assures the system is designed for supportability. In terms of the building system, this means consideration of building logistics and maintenance requirements as well as maintenance and logistic support during construction.

5.5.3 Life-cycle Cost

The effectiveness of a building system can be judged in many ways most of which are subjective (functionality, aesthetics etc). The most objective means to evaluate a system is by means of economic analysis. "There are numerous

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[11]Blanchard, page 12.

examples of structures, processes and systems that exhibit excellent physical design but have little economic merit. The essential prerequisite of successful engineering application is economic feasibility."[11]

The economic environment of a building project can not be separated from the physical environment. Delivery of building systems is a business; a business must profit; the consumer must be satisfied to profit. As milton Friedman, the 1976 Nobel Prize winning conservative American economists states, "business' sole responsibility is lawful profit maximization."[11] The construction industry is no exception to this basic capitalist philosophy. The ability to understand the economic "facts of life" is vital for all construction proprietors due to the critical role the industry plays in the American economy. The basic principles of engineering economy and the time-value of money affect a system's profitability over each phase of the life-cycle.

The monitoring and control of cash-flow is a basic accounting tool for determining a firm's financial status. "The net cash flow stream, a discrete or continuous function of time, is the basic economic measure of a project used to

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[11]Fabrycky and Blanchard, page 1.16.

[11]McAdams, Tony, Law, Business and Society, Second Edition, (Homewood, Ill: Irwin, 1989), page 119.

determine its profitability to a firm."[16] Because of the nature of a construction firm's organization and operation, standard accounting methods used by other industries fall short of the contractor's needs. "The contractor takes on contracts, lets contracts, purchases materials and employs labor on a number of jobs at one time"[17] each requiring separate documentation and division of costs. A firm's profitability and financial status becomes the amalgamation of each of the on-going projects.

Because of these operational and organizational differences, a construction firm is more sensitive to an individual project's cash-flows then other manufacturing industries. The cash-flow stream within a firm is modified by the projects it undertakes; and the cash-flow is an integral component of the firm's overall functional investment, financing and producing cycle (Figure 10).[18] A manufacturer can usually recover from an unprofitable product line, but the contractor can not afford many unprofitable projects. The contractor's low volume and high investment in

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[16]Bussey, Lynn E, The Economic Analysis of Industrial Projects, (Englewood Cliffs, NJ: Prentice-Hall, 1978), page 29.

[17]Walker, Frank R, Practical Accounting and Cost Keeping for Contractors, (Chicago, Ill: Frank R Walker Company, 1975), page 1.

[18]Bussey, page 18.

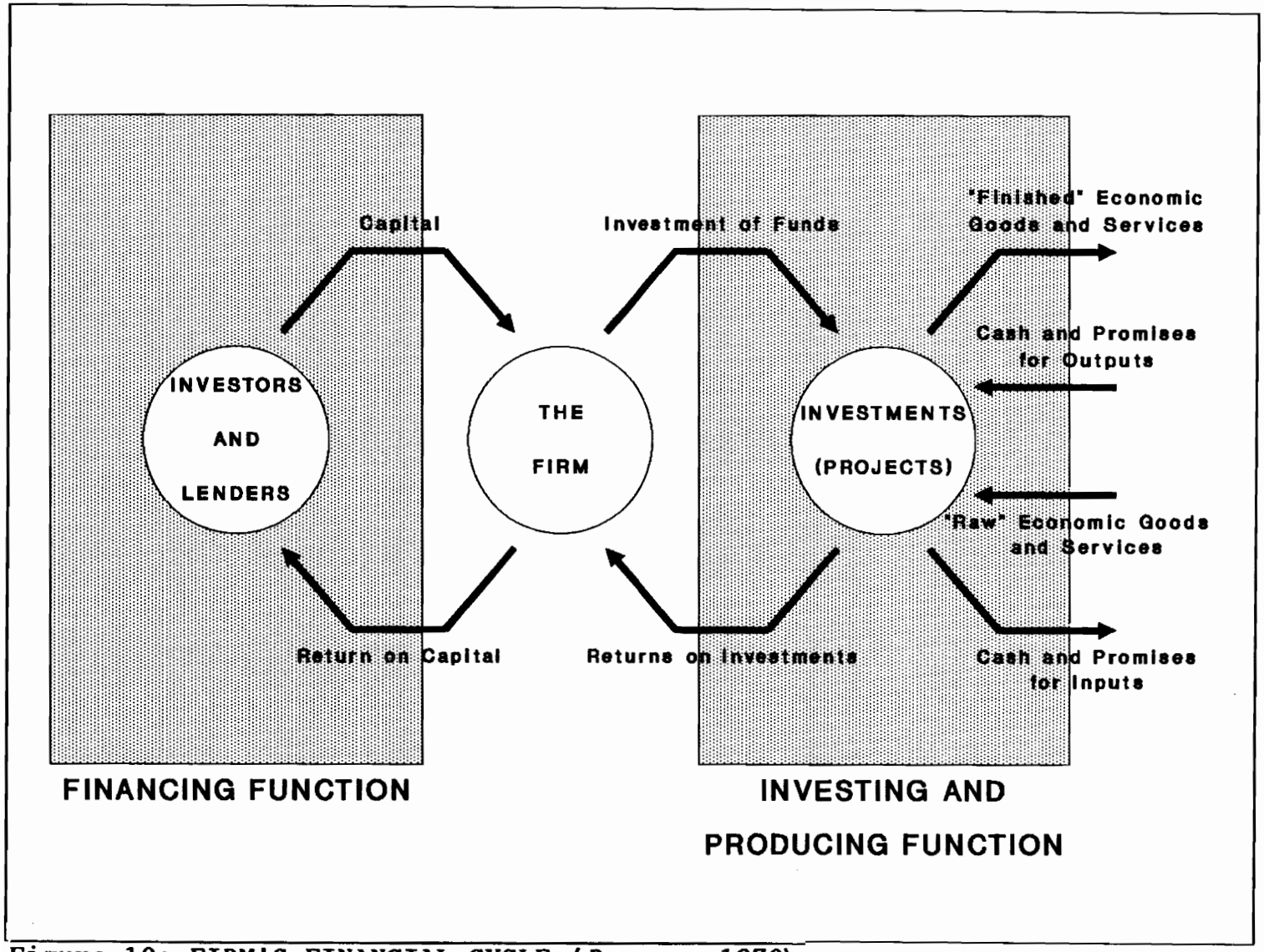

Figure 10: FIRM'S FINANCIAL CYCLE (*Bussey, 1978*)

each product ties the firm's success to each endeavor's cash-flow.

The cash-flows of a project must balance between the expense incurred and the revenue received. As a project grows in scope and complexity, the required capital investment ("up-front" money) typically increases. This investment capital is generated through the use of previous profits, use of investor capital, and/or borrowed funds. The revenue received from the project must cover the expenses of the project (materials, labor, equipment, taxes, bonds, etc), the repayment of investments, the payment of interest and profit on the investments (Figure 11). Failure to balance these flows leads to financial failure.

Cash-flows do not remain static during their transition through the project. The pure exchange of capital (goods and services purchased to goods and services sold) is altered by the effects of the economic environment over the time period the cash-flow is involved in the project. The net value of a cash-flow is typically reduced by these factors over time. This phenomena is caused by the earning power and purchasing power of the cash today versus the cash at some future time. The more volatile the effects of the time value of money is on the cash-flows of a project (due to the length of the commitment, risk of failure, inflationary atmosphere, high

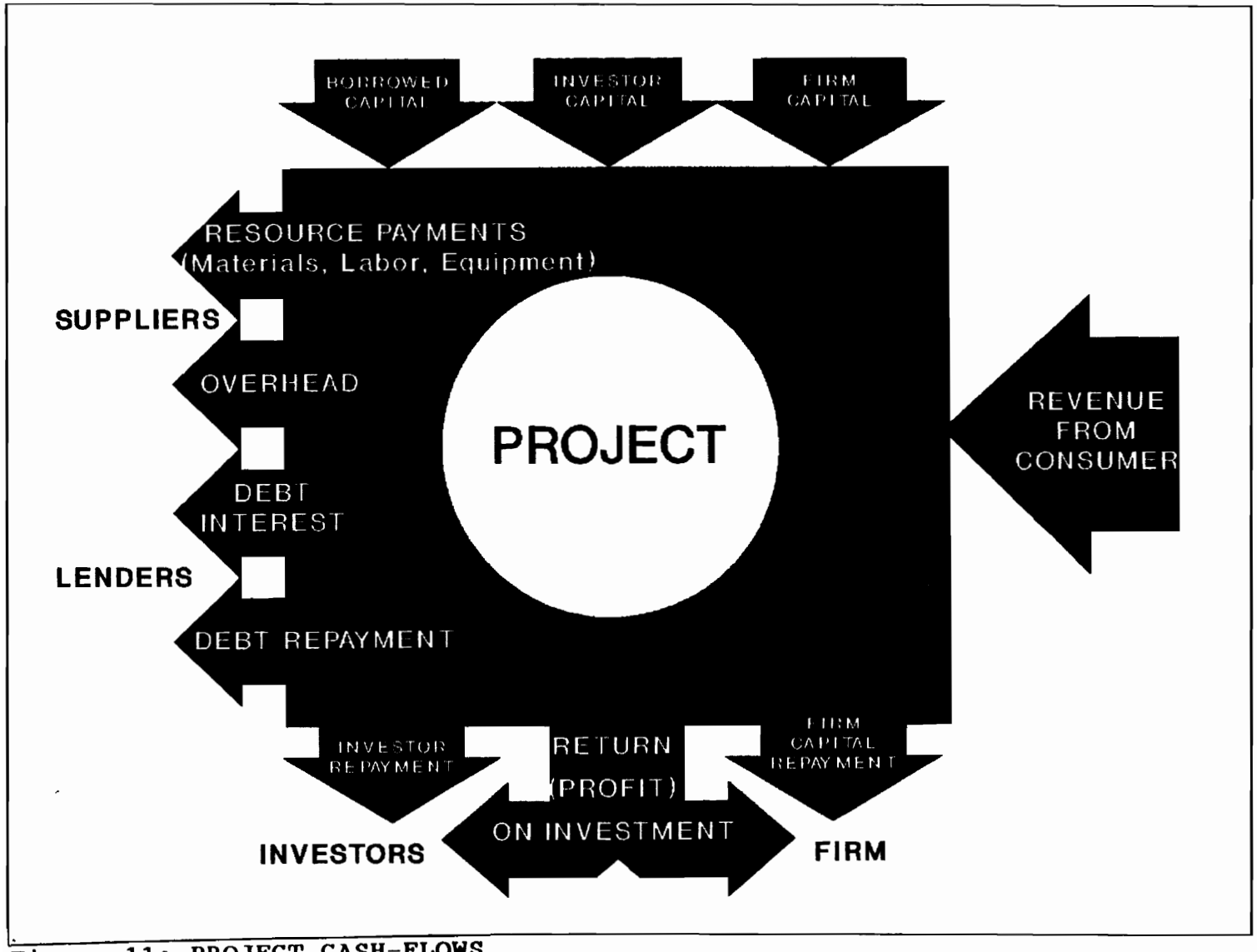

Figure 11: PROJECT CASH-FLOWS

interest on borrowed capital, etc), the more important it is for a firm to manage its capital flow. A poor estimate of the effect of these conditions on the value of a cash-flow can reduce or eliminate a firm's profit and lead to business failure.

5.5.4 Systems Engineering Management

Since Systems Engineering principles are designed to ease the complex communications problem caused by large scale projects involving several distinct parties and disciplines, the organization of the design and delivery team is crucial to success. "Systems engineering management involves the planning, organizing, staffing, monitoring and controlling the process of designing, developing and producing a system that will meet a stated need in an effective and efficient manner."

An effective management plan must identify tasks, milestones and responsibilities, but more over, it must recognize the integration of the tasks developed by specific engineering disciplines into an overall product. The organization for the execution of the project must be organized by functions, with disciplinary interfaces at appropriate levels for the delivery of functional activities. Milestones and activities are organized by functional interaction using network scheduling tools (PERT, CPM, Gantt,

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"Blanchard and Fabrycky, page 546.

etc). The management and organization of the Systems Engineering approach is designed to exploit the benefits of each discipline while assuring a functionally focused team effort."

5.6 SUMMARY

The methodologies and tools of systems engineering can be readily applied to the construction process. The current life-cycle of the construction process is fragmented with minimal interaction between disciplines and a minimum regard for the product operational requirements after delivery. In the construction industry, there is no use of prototyping, the end product is the prototype. Because of this the application of Systems Engineering methodology to highlight interaction and expose concerns will prove valuable.

The development of the *Total Life-cycle Construction (TLC)* approach will combine current tools and practices of the construction industry with the principles of Systems Engineering to develop a new information management for the delivery and operation of building systems. The major focus of this approach will be the infusion of life-cycle and logistics concerns into the construction process. The

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"Blanchard and Fabrycky, pages 548-558.

computer-based tools available today will yield a formwork to facilitate both communications and control of the *TLC* approach to construction. The *TLC* concept is presented in Chapter 6 and further developed in Chapter 7.

VI. THE *TLC* CONCEPT

"There is nothing permanent except change."
- Heraclitus[91]

The construction industry of today is at a crossroads of development. Just as the industry of a hundred years ago was altered by organizational changes and technical advances, these same factors will require a controlled modification of the industry's approach to business tomorrow. The isolation of design professionals from production and advances in computer based technologies will mold the future shape and approach to business of the construction industry.

The problems associated with the industry's evolutionary process could be avoided by viewing the construction project as a building system and applying the Systems Engineering principles of life-cycle management and the team approach to the final product. Many of the problems of the past were the direct result of the poor communications procedures applied within the construction process. These communications problems were the result of poor information dissemination and confusion and overlap in the roles and responsibilities of the participants in the process.

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[91]ELIA, page BT-67.

Past or current attempts to improve organization or modify operations through technical changes represent a piece-meal approach to evolution, adding tools and modifying organizations with each new development or challenge. There is no simple way to correct these inherent organizational problems; short of a total reorganization of the construction industry's management of change and improvement of communications. *Total Life-cycle Construction (TLC)* is a theoretical concept for improved information management in facility design, delivery and operation. *TLC* also provides a methodology to allow early identification and mediation of the impacts of facility changes.

This chapter will apply the principles of Systems Engineer to identify the functional requirements and information interfaces within the life-cycle of a facility. The concept of interaction and feedback between the major participants within the development and operation of the facility forms the basic framework for *TLC*. This interaction and feedback is coupled with the requirements of the facility's life-cycle to develop the functional interactions and process flow of the facility's design, production, operation, maintenance and retirement. The identified functional requirements will then be incorporated into the *TLC* information interface system developed in Chapter 7.

6.1 *TLC* FRAMEWORK

TLC is a hybrid of current approaches to the organization of functions and activities for the delivery of the building system. Containing elements of previous organizational structures (Professional Construction Manager, Master Builder, Design-Construct), it represents a new method for information management. *TLC* is envisioned to exploit current and potential computer technology and management tools to simulated a facility prototype over time and control production (construction) and operation. *TLC* proposes an information management and transfer network approach to the construction communication process with the intent of reducing, managing and responding to change within the context of the facility's total life-cycle. By applying the principles and tools of Systems Engineering, a philosophy of the delivery of structures can be formulated around the requirements and knowledge bases of the three major elements in the process: the Functional Requirements, the Design Parameters and the Production Parameters. (Figure 12).

6.1.1 Life-cycle Environment

First and foremost, *TLC* involves the interaction of the three elements in each phase of the life-cycle of a facility.

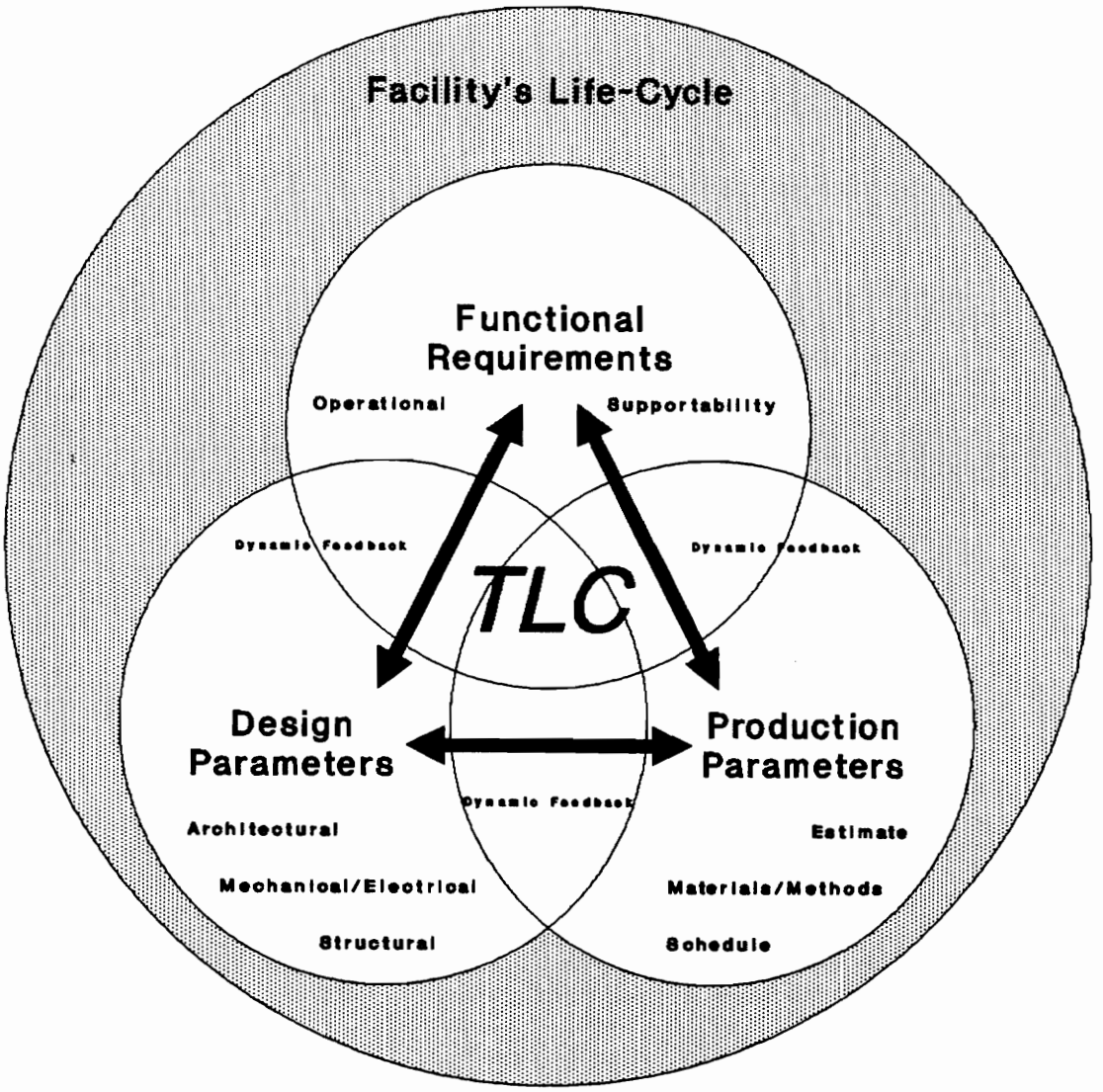

Figure 12: THE *TLC* FRAMEWORK

The consumer's and producer's (constructor's) needs and requirements are just as valid or critical in the design phase as the designer's input. Similarly, the designer's input and concern must not stop with the delivery of the drawings and specifications to the owner. *TLC* develops a framework to implement interaction an feedback not only between participants, but also life-cycle phases. The supportability and operational requirements of the structure must be considered in design and construction; construction concerns must influence design, and all phases are based on identified needs and requirements of the structure.

TLC could allow any of the participants within the process to both input as well as update data. Because of the interactive nature of the system, modifications to previously accepted data will immediately illustrate the overall impact of the proposed modification on all elements and throughout all phase of the life-cycle. An object-oriented approach could reduce the delays and costs of later changes by highlighting the impacts of change in a simulated facility model early in the design process. This prototype simulation will be further developed in Chapter 7.

6.1.2 Functional Requirements

Traditional design approaches all begin with the determination of the consumer's needs and the identification

of design criteria or limitations.[11] The early phases of any project design include determining such things as spacial requirements, building functions and cost limitation. With this information, the designer can begin the preliminary design of the structure. The current means of determining these requirements is often subjective, and specifically focused to operational spacial requirements. The consumer's needs go beyond this traditional design input.

The process of inputing the consumer's needs must be formalized. While the current method of determining needs is an adequate beginning point, as the design process matures consumer input must not end. The consumer should be the designer's partner, imputing operational and supportability requirement continually as the design develops. In deciding the mechanical system for the building, initial and changing consumer requirements for maintenance access, replacement and utility costs must be incorporated. The consumer, just as the other participants, must be made aware of the overall life-cycle impacts of desires and changes on the facility. Through the prototype simulation, design tradeoffs to reduce life-cycle costs (including maintenance, operation and support) must be included in all phases.

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[11]Hanks, Kurt, Larry Belliston and Dave Edwards, Design Yourself!, (Los Altos, CA: William Kaufman, 1977), page 60.

6.1.3 Design Parameters

The designer, more than either of the other participants has the greatest ability to reduce life-cycle cost of the structure. By considering all aspects of the life-cycle and imputing requirements feedback from the producer and consumer, the designer can develop a building plan which eliminates conflict and confusion during construction and dissatisfaction during operation. The designer's parameters represent a highly specialized interrelationship between many technical and engineering professionals.

The designer must consider the input of not only the producer and consumer, but also the requirements of the engineering disciplines and the restrictions of the building site and the restrictions of local building regulations. The architectural requirements of the structure is not limited to the aesthetic aspects of the design but must incorporate the safety and human factors concerns as well as manage the interface of the structural, electrical and mechanical systems of the building. The structural, electrical and mechanical designs represent a subsystem input to the overall structure which must include feedback and input from the three major participants over the entire project's life-cycle. All the design parameters must consider the life-cycle implications of the constructability requirements of the producer and the

operational and supportability concerns of the consumer in their design development.

6.1.4 Production Parameters

Like the designer, the producer must manage the input and feedback of several specialized subsystem providers in controlling of the construction. The producer provides the major interface with material suppliers and the labor force. The producer has the most significant input on total project life-cycle cost, since the construct phase represent a significant component of the capital expenditure of any project. The producer's input to material selection and the control of the means and methods of construction significantly affect design and execution of the project.

The producer's accurate estimating and scheduling of activities and cost can determine the success of not only the construction firm (Chapter 3), but also the success of the project itself. The accuracy of the producer's plan and its input into the design phases can significantly reduce the project's life-cycle cost, by reducing costly (both in terms of time and money) changes during construction. The producer's quality control interface with the consumer can reduce the life-cycle cost impacts of maintenance repair and operational utilities, while enhancing user satisfaction.

Through prototype simulation, the producer can visualize

the construction of the facility in a manner similar to the consumer's visualization of the facility's operation. Methods of construction and scheduling trade-offs can be evaluated and incorporated early in the facility's life-cycle. The impacts of design or operational changes on the construction of the final facility can be readily highlighted and incorporated in the production plan without the costly delays of the current procedure.

6.2 *TLC* LIFE-CYCLE

The integrated life-cycle approach is not typically applied to the delivery of building systems. Because of the nature of the industry, design and production activities have minimal interaction, and consideration of post-delivery support of the system in design and construction is virtually non-existent. Duties and responsibilities are identified and isolated within specific disciplines (architects, engineers, contractors, sub-contractors, consultants, etc.) Each party is independently responsible for specified actions within each phase in the life-cycle. Typically there is minimal interaction or feedback between the participants or functions. This isolation is heightened as the project evolves through the life-cycle with no single party responsible for overall

integration of the elements, save the consumer or owner.

The first step in developing a new system of construction is to recognize the elements of the system's life-cycle. Figure 13 represents the facility's *TLC* phases. The life-cycle approach to any problem views the development of the product from "the cradle to the grave." The cycles or phases of the life-cycle are defined as: design (conceptual, preliminary and detailed), production or construction, the operation and support of the facility, and culminates in the retirement and disposal of the system.

In the construction process of today, roles and responsibilities are fragmented between both practitioners and phases of the life-cycle. As illustrated in the Hyatt case[11], this leads to poor communications as more consultants are employed to handle the evermore complex technology of building delivery. The goal of *TLC* will be to significantly reduce the disciplinary barrier between life-cycle phases and to incorporate the requirements and inputs of each discipline and each life-cycle phase into the final product.

The various industry tools, both traditional and computer applications, currently available support functional tasks associated with each of the life-cycle phases. These tools, along with current communication and computer technologies can

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[11]Hein and Beliveau, page 70.

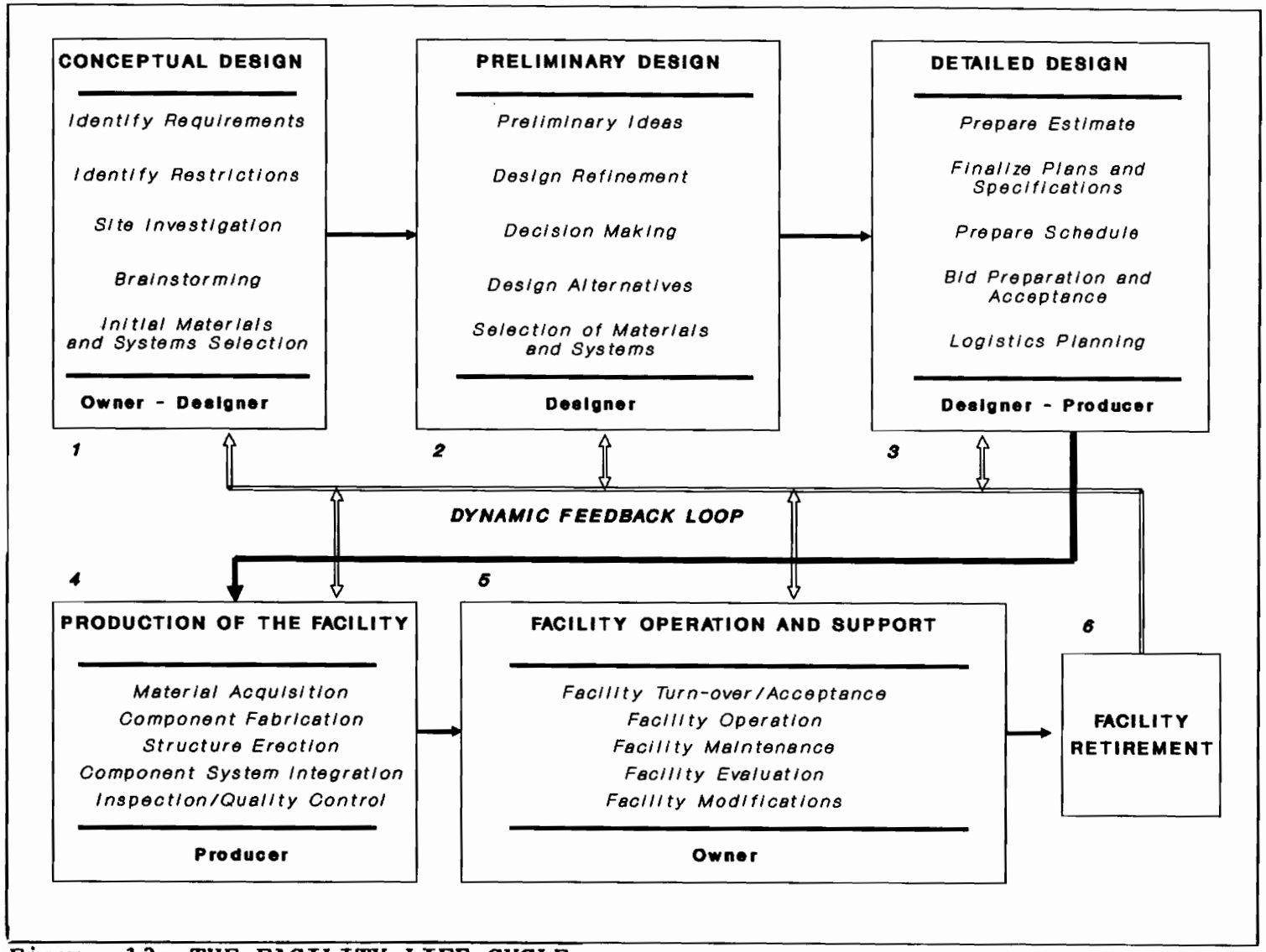

Figure 13: THE FACILITY LIFE-CYCLE

facilitate the rapid transfer and sharing of information across disciplinary lines and life-cycle phases. Current application of these tools, just as with the early application in industrial robotics, is to replace traditional practices and actions rather than the development of new methodologies. This leads to a piece-meal application of these new functional tools. *TLC* develops a methodology to structure the interaction of these tools to facilitate product development, production, operation and support across the entire projects life-cycle. The development of an interactive system based on functional requirements rather than the automation of current practice will improve both industry communication and the ability to respond to change.

6.3 *TLC* FUNCTIONAL FLOW

The functional flow process is used to logically determine and diagram required processes, interfaces and data input or output during the development of a system. The procedure involves identifying top level functions, then developing those function through a series of increasingly more detailed functional flow diagrams. As the detail increases, required information transfer, operational tasks and maintenance actions can be identified. For the *TLC*

information management process, the functional requirements of the current design, production and operation procedures of facility development are used as the basis for the development of the system's requirements.

The *TLC* Functional Flow (Figure 14) begins with the identification of nine primary actions required to delivery a building system. *TLC* builds on the basic accepted principles of building delivery, while incorporating feedback and interaction into the process. This view of the facility life-cycle is not radically different then those readily accepted within the construction industry.[11] Were the *TLC* concept differs is in the depth it analyzes the communications and interrelationships within the functional flow of the life-cycle stages and its incorporation of life-cycle logistics and cost considerations. Figures 15-20 will expand the functional activities within the basic facility design, delivery and operational functions of the facility life-cycle.

Although these basic functions within the facility's life-cycle are present today, they are rarely incorporated into a holistic approach. This fragmented application of the required function leads to poor communications and therefore costly changes. The process is not linear, although it develops over time, feedback requirements as well as

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[11]Hendrickson and Au, page 3-4.

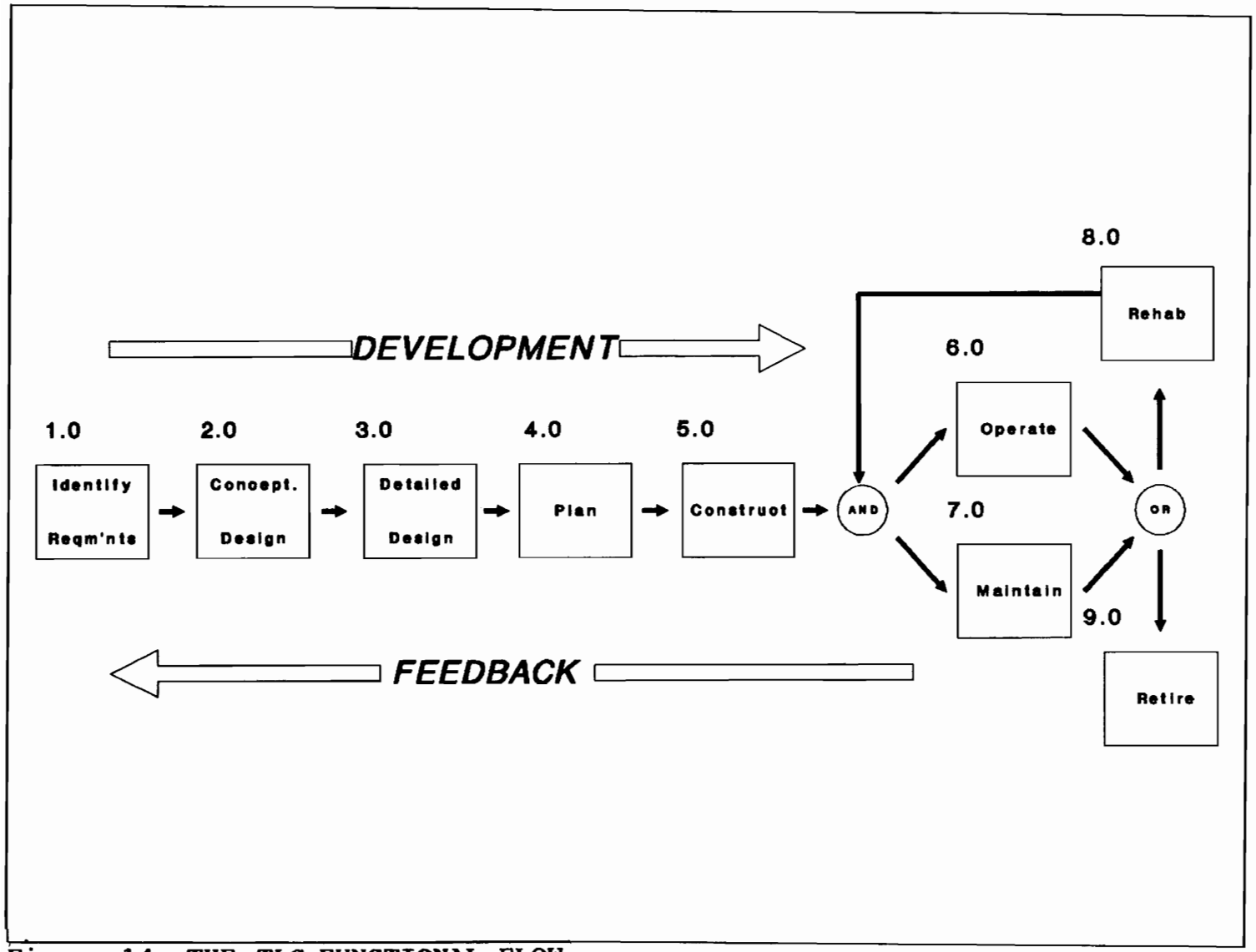

Figure 14: THE *TLC* FUNCTIONAL FLOW

modifications, will alter previous decisions. An effective information management system must recognized both feedback and change input to the system.

6.3.1 Identify Requirements (Figure 15)

No system can be brought into existence without a thorough understanding of the consumer requirements and legal or physical restrictions of the project. Figure 15 expands Block 1.0 (Identify Requirements) of Figure 14. This portion of the *TLC* concept formalizes the information gathering and requirements identification functions of the current design process. This phase is intended to expose the developmental process of the building to operational, budget, construction, logistics, environmental and legal concerns in the earliest stages of development. The final product of this function is the *Building Requirements Program* document/data base which is used throughout the remaining phases to evaluate the design.

The first step in this process is the determination of the consumer's requirements and restrictions on the building development. This is accomplished through identifying the functional requirements of the structure and determining the budgetary constraints of the project. These two basic pieces of information allow the development of operational requirements and the initial maintenance concept and logistic support for the facility. These general requirements allow

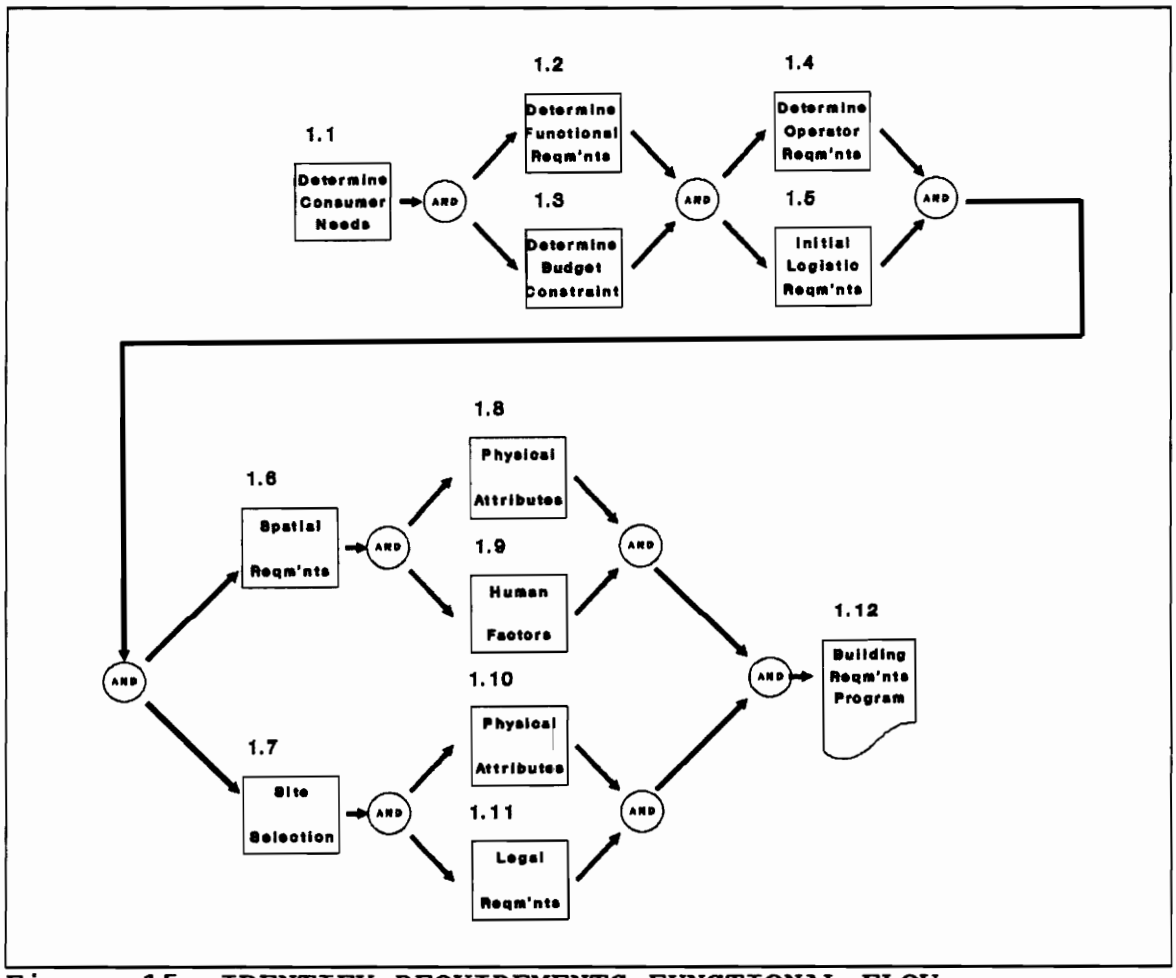

Figure 15: IDENTIFY REQUIREMENTS FUNCTIONAL FLOW

the development of initial spatial requirements and the selection of the building site. The spatial requirements of the facility is molded by the interaction of the physical requirements (size, type, location, relationship, etc) of the spaces and the human factors concerns (operator/maintainer tasks, operational/maintenance/handicap access, system safety analysis, etc) of the spaces. The site selection yields two critical portions of the building program; the physical

attributes of the site (size, location, environmental conditions, etc) and the legal requirements of the building (zoning restrictions, code requirements, environmental impact, etc). With the facility requirements program (Facility Program) developed, the *TLC* team can continue the design process.

6.3.2 Conceptual Design (Figure 16)

The conceptual design phase of any process represents the most creative segment of the overall design process. Figure 16 expands Block 2.0 (Conceptual Design) of Figure 14. With a good understanding of the project's problems, requirements and restrictions (Building Requirements Program), alternative ideas for solutions can be developed.[11] Brainstorming of ideas and evaluation of alternatives requires the participation of each of the three members of the *TLC* triad (consumer, designer, producer).

Alternative concepts are developed and considered in terms of functional organization, initial materials selection and building support systems (structural, mechanical and electrical) concepts. The alternative conceptual designs are evaluated against the requirements of the Building Requirement Program. Concepts are reviewed and analyzed in terms of the program (operational and legal requirements), the budgetary

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[11]Hanks, Belliston and Edwards, page 60.

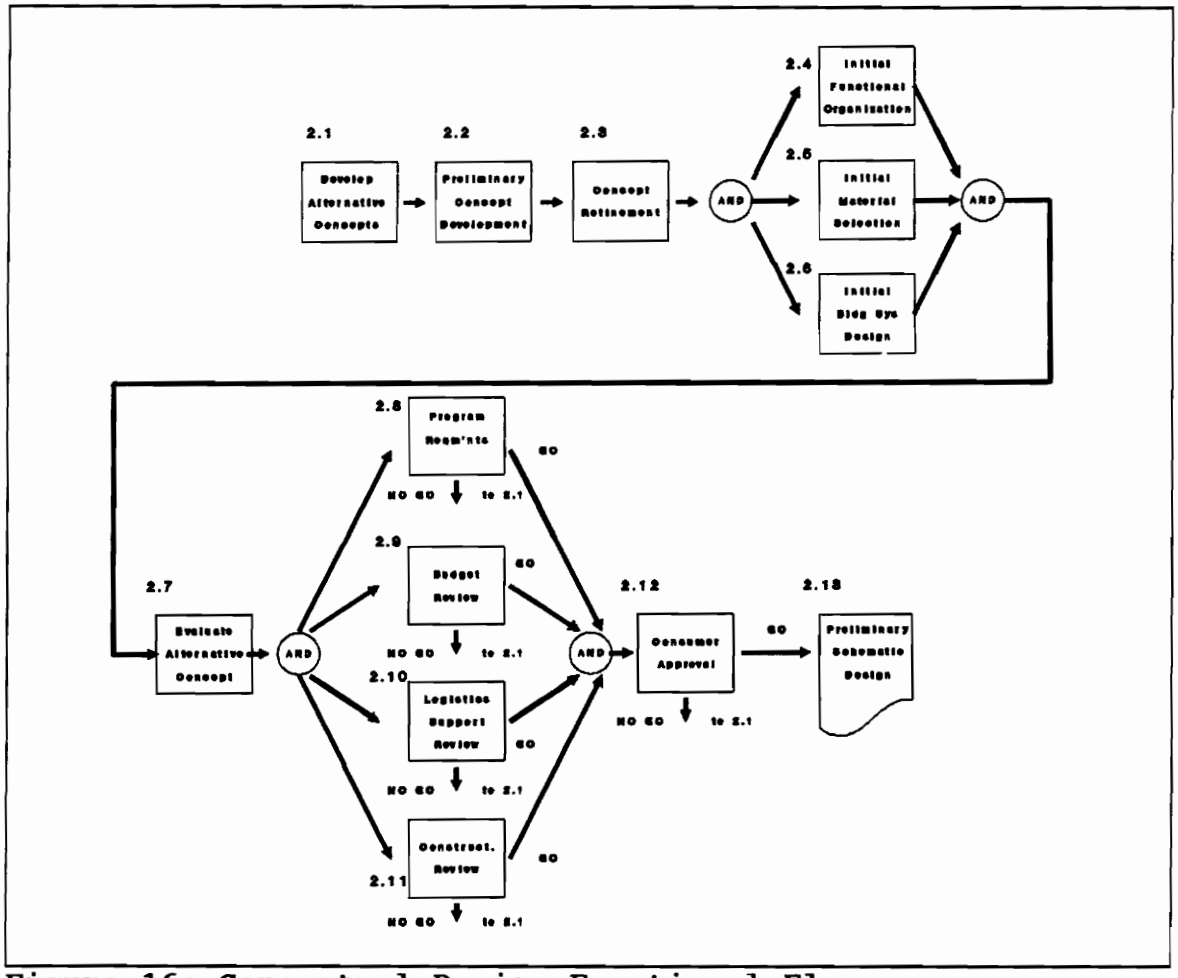

Figure 16: Conceptual Design Functional Flow

constraints based on a design estimate, the logistics support requirements of the design and a review by the producer element of the concept's constructability. The LSA at this phase examines gross support requirements (utilities costs, maintainability trade-offs, etc). The final analysis before the production of the preliminary schematic design is the consumer's review and approval. If a design alternative fails to meet the program requirements or fails to gain the

consumer's approval it is rejected and the process begins anew. The iterative nature of the design cycle continues throughout the design process. Computer simulation of alternatives can significantly reduce the impact of modifications on the project's life-cycle costs, especially if included early in the conceptual design process.

6.3.3 Detailed Design (Figure 17)

With an approved preliminary design in hand the detailed design process can begin. Figure 17 illustrates this process by expanding Block 3.0 (Detailed Design) of Figure 14. The detailed design process resembles the conceptual design process in many aspects. Both processes refine and evaluate the design with regards to the program requirements. As the name implies, the detailed design is concerned with the development of detailed aspects of the final design. The structural, mechanical and electrical components of the design are engineered and specified. The architectural concerns of the design (human factors, safety, aesthetics, landscape, etc) are also designed and specified. These contributory plans are then synthesized and reviewed, checking for conformity to concept, accuracy and to resolve conflicting requirements between components.

After integration, the design is reviewed and approved against similar criteria as the conceptual design. The budget

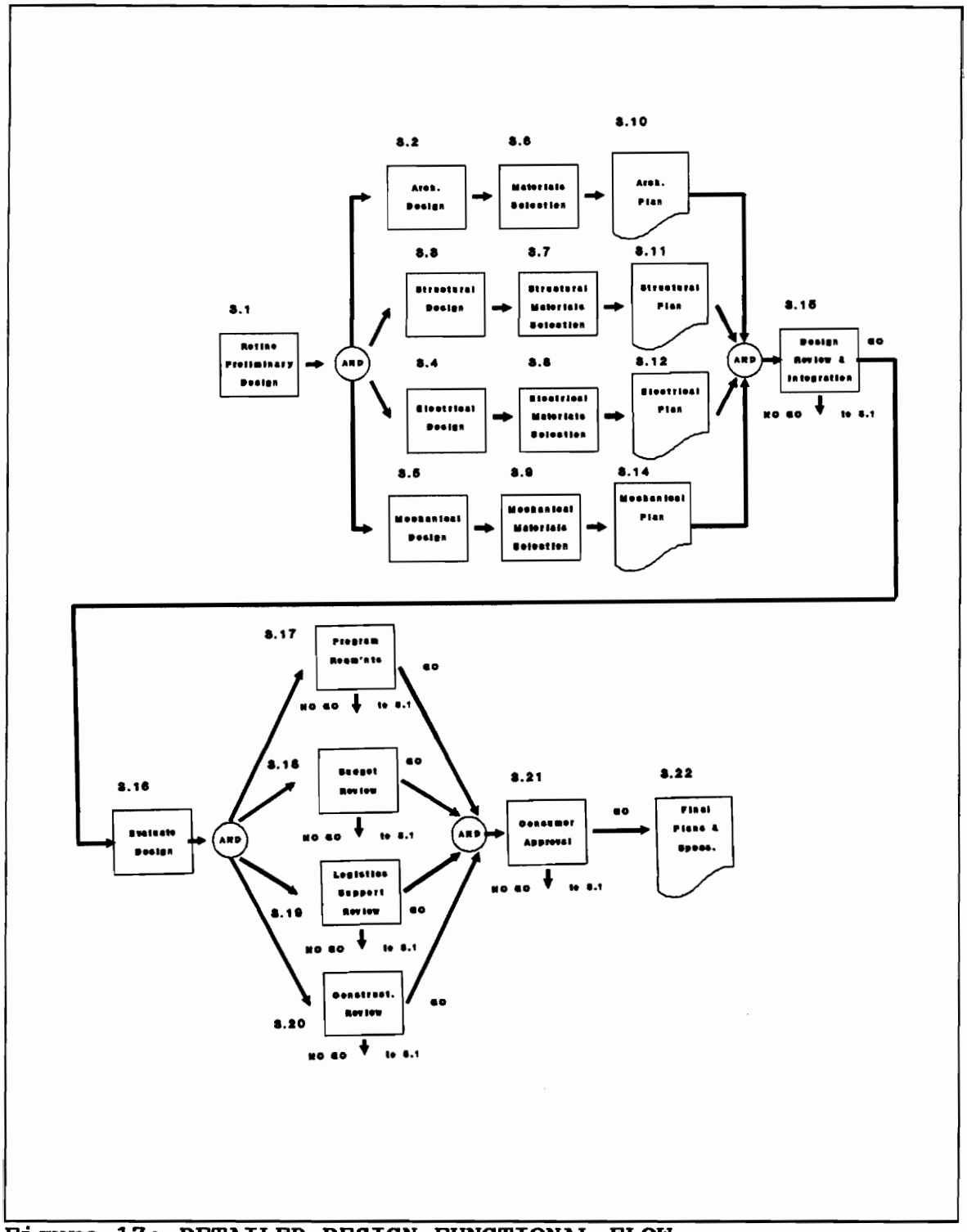

Figure 17: DETAILED DESIGN FUNCTIONAL FLOW

review at this stage allows for the development of a design estimate for use in financial planning and acquisition for the project. The logistic support requirements at this phase is more finely developed, considering both the maintenance and support requirements of the proposed design, and also expanding into an initial maintenance and logistic concept for the construction phase. The Logistic Support Analysis (LSA) is discussed in more detail in Chapter 7. The Constructability concerns of the producer are incorporated in the review to reduce future conflicts and change requirements. Design elements which fail to satisfy constraints or requirements of the program are refined until an optimal design is determined. Following the approval by the consumer, the design is finalized and plans and specifications for construction are produced.

6.3.4 Plan (Figure 18)

As important as an integrated design is to success, a well developed plan can highlight and avoid conflicts or problems, saving both time and money during the construction phase. The functions included in Block 4.0 (Plan) of Figure 14 are illustrated in Figure 18. The *TLC* planning process is intended to develop an accurate schedule for construction as well as construction cost control and quality control plans, all of which can be used to monitor and evaluate the execution

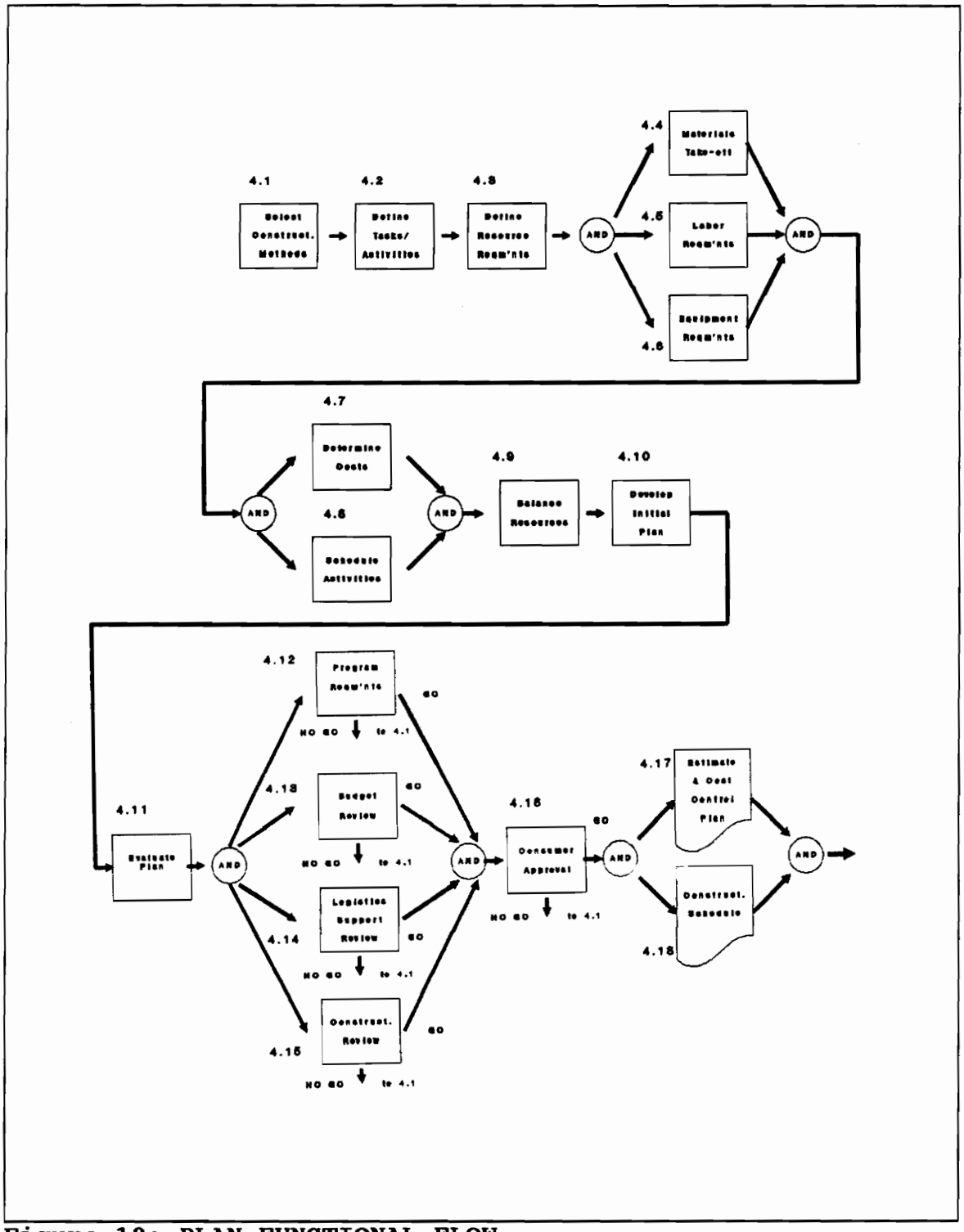

Figure 18: PLAN FUNCTIONAL FLOW

of the project.

The *TLC* planning function includes the traditional construction management functions of estimating costs and scheduling activities. The type, amount and cost of resources are determined and integrated into the logical sequences of construction. The traditional tools of CPM analysis can be used to both schedule the construction process and level resource requirements. This time-sensitive cost information can then be used to develop an amortized cost estimate and the Life-cycle Cost Control model (LCC). The LCC model is discussed in more detail in Chapter 7. The end results of this process are two key documents/data bases; a proactive construction schedule and a life-cycle cost model for both bidding and cost control of the project.

The plan, schedule and estimate are again evaluated against the requirements of the program, budget, logistic support concept and the constructability of the plan. The constructability analysis reviews the logical sequence of the construction process and assures a smooth execution. The Logistics Support Analysis (LSA) at this level concentrates on the logistics support required to maintain construction equipment as well as procurement, transportation, storage and inventory control of the construction material resources. In general, the plan cycle converts the approved design to an

executable entity.

6.3.5 Construct (Figure 19)

TLC does not modify the physical actions of construction,

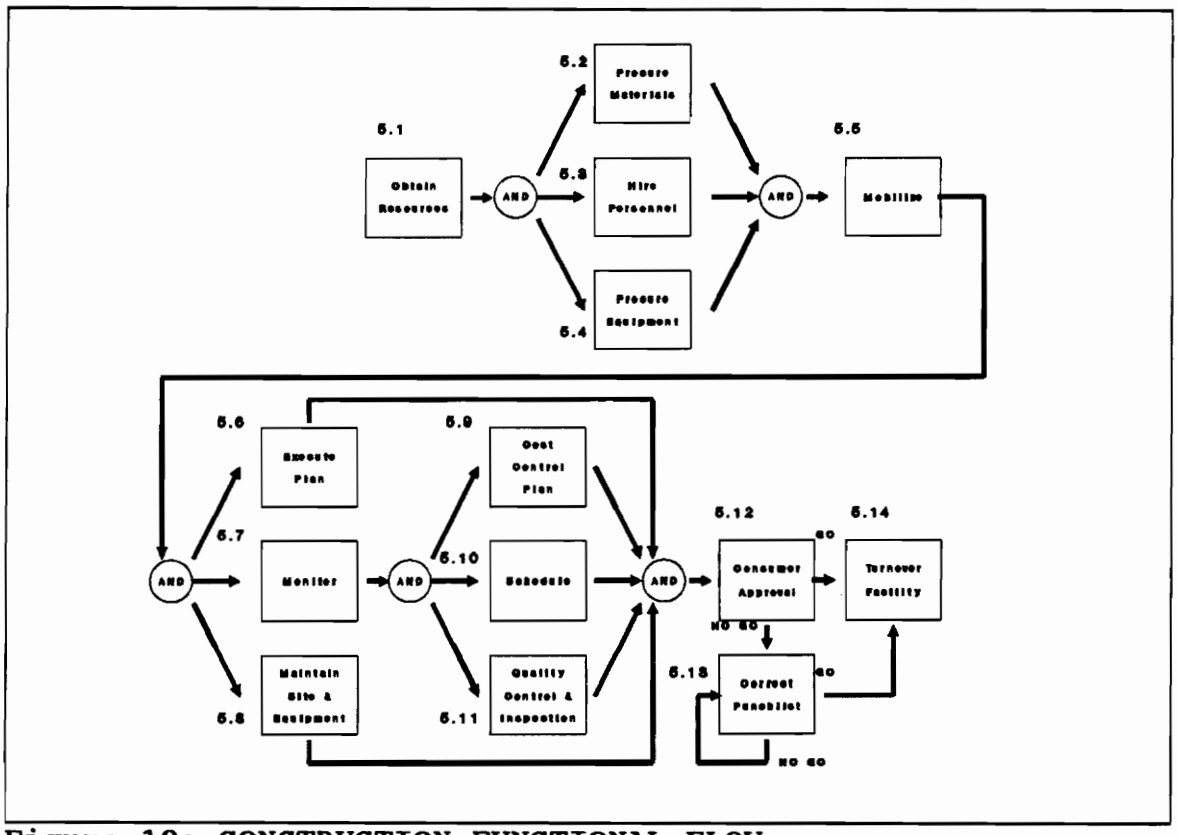

Figure 19: CONSTRUCTION FUNCTIONAL FLOW

rather it address methods of controlling these processes. These process relationships, identified in Block 5.0 (Construct) of Figure 14 are expanded in Figure 19. This includes the control of the resources as well as the control of personnel and equipment involved in the construction process. The acquisition, storage and management of materials

in terms of inventory control and site usage and position is considered. Personnel and equipment resources are staffed, both in terms of indigenous manpower or equipment as well as leased or subcontracted work.

The process of construction is controlled and evaluated in conformance to the schedule and cost control plan developed in the planning phase, with the ultimate goal of delivery of a cost effective structure which meets the requirements of the consumer in a timely manner. The work completed is compared to planned activities or resource requirements. Feedback then facilitates the revision of planned activities and requirements.

6.3.6 Operate and Maintain

The operational support functional flows of the process will change with the operational characteristics of each project. These functional flows will play a vital role in the development of consumer requirements and play a major role in the evaluation of design alternatives. Although operations and maintenance may represent a small percentage of the facility's life-cycle cost (when compared to the cost of design and production of the facility), they represent the longest component of the systems life span. The requirements, needs and desires of the consumer as they relate to these phases significantly affects the design and development of the

structure.

The most important function during the operation and maintenance of a facility is the integration of asset management with logistic support. Regardless of the size, scope or location of a facility, its spaces and real estate represent assets. Whether the facility is public or private, single-use or multi-use, the consumer must have a tool capable of maximizing satisfaction (profit), minimizing support costs and forecasting requirements. By orienting the developmental requirements logic graphically to spaces and elements within the facility, future modifications or additions to the facility can be linked to the original *TLC* system logic to optimize options and operations.

6.3.7 Rehabilitate and Retire

Just as with Operations and Maintenance, Rehabilitation and Retire functional flows are unique processes within specific projects. Consideration of the disposition of the system following its intended use is vital in these times of growing environmental awareness. Will the structure be modified for further use of become a slum; if demolished, will the materials be reused or add to our increasingly overcrowded landfills. These retirement conditions can significantly affect design, cost and operational considerations within the life-cycle development. The only feasible way to assure user

satisfaction with the final product is to incorporate these post-delivery considerations early in the life-cycle development of the project.

Facilities are not all retired after their originally intended use is completed. Owners of structures typically replace or modify the functions housed within the facility over its life-cycle. These modification can be initiated by changed operational requirements or by replacement with a totally new consumer. Rehabilitation or retrofitting of facilities represents a major cost contributor within the systems life-cycle. Figure 20 illustrates the functions contained within this redevelopment of a facility originally

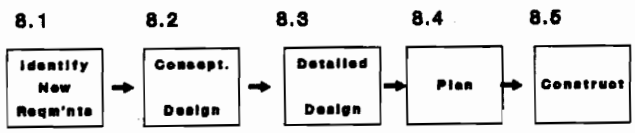

Figure 20: REHABILITATION FUNCTIONAL FLOW

identified as Block 8.0 in Figure 14. These functions are virtually identical to those executed in the original design and delivery of the system, although they may have a modified scope.

6.4 SUMMARY

History has shown that poor communication between the participants in the construction process can lead to disaster. Timely information, accurately delivered to the right person is knowledge, and in this case knowledge is power. It is not only the power to avoid catastrophe, but the power to recognize, react and reduce changes in the construction process. The ability to control change, while delivering the desired product, will significantly reduce life-cycle costs while increasing user satisfaction with the final product.

Together, the system's complete life-cycle development and its required functional flows form the basis for the management of required information interactions between the *TLC* participants. This information management can make the knowledge of the facility's requirements a powerful tool in controlling development. The integration and feedback of the data derived and collected during each phase of the project's life-cycle form this information is need to adequately derive the operational and support requirements for facility.

This chapter has developed the functional requirements of a revised communication process for the design, production and operation of facilities. By applying the life-cycle and functional flow principles of Systems Engineering, the

required information interfaces within the facility design, delivery and operation process have been illustrated. In the next chapter, these requirements will be translated into a model for *TLC* information management. This model will provide facility prototype simulation, required documentation and provide a methodology to control the impact of change. facility production and operation in the twenty-first century.

VII. *TLC* DEVELOPMENT

"Knowledge is of two kinds, we know a subject ourselves, or we know where we can find information upon it."
- Samuel Johnson[16]

Data is only information when it is properly communicated to the correct person in a timely manner. Today's construction industry does not foster this development and communication of information. Problems and changes occur as a direct result of poor information transfer. Any revision to the methodology used to deliver the building system must address both information interfaces with the users and the means to facilitate change. In this chapter, the *TLC* system requirements identified in the previous chapter will be developed into a model for facility information management.

Changes and delays in the delivery process of the building system represents one of the most costly occurrences in the project, both in terms of time and money. "It is rare indeed if a construction project is completed without changes being made"[17] Changes and delays initiate at three primary sources; those beyond the control of the consumer and producer ("Acts of God"), those under the control of the consumer, and

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[16]ELIA, page BT-80.

[17]Nunnally, page 418.

those under the control of the producer. Consumers often require revisions to the structure or finishes during construction while producers are unable to execute their plan due to modified conditions. The costs and delays associated with changes are a result of the construction system's current difficulty in communicating between participants and the inability to prototype projects for evaluation.

Now let's picture that futuristic concept of facility delivery envisioned in Chapter 1 again. A consumer, design and producer interact with computer system. Each participant inputs his specific facility requirements. The system then generates a facility image which proceeds through the entire life of the facility. The producer sees the time lapsed erection of the structure; the design sees functional and spacial relationships and finishes; and the owner sees the facility in fully operation down to the performance of maintenance. Conflicts and problems are rapidly identified and correct, a new concept is developed then evaluated. All accomplished before soil is turned. The facility is constructed and operated, all controlled and evaluated by the same information base. This is the envision operation of *Total Life-cycle Construction (TLC)*.

The information processing which makes up the *(TLC)* approach to building delivery could be a manual process,

however the ever growing role of computers in the construction industry makes this option unnecessary. With this technology in mind, *TLC* can become an interactive object oriented data base management network which responds to the functionally developed information requirements of both the construction and facility support process. *TLC* incorporates information and requirements with graphical objects. Through this process, later changes of graphic objects will immediately flag all historical information on the development of an object so as to require and facilitate decisions on change impact throughout other phases and life-cycle requirements.

TLC will allow for facility prototyping via CAD-based three dimensional animation of all aspects of production and operation of the project. With this simulated facility, changes can be identified and adjustments can be made early in the design process thus reducing or eliminating physical changes totally. From this information interaction; tools to control production, evaluate alternatives and maximize life-cycle utilization and management of the facility are possible.

7.1 *TLC* PROTOTYPE SIMULATION

In the past, there have not been satisfactory methods of representing either the delivery process, design configuration

or operation of an intended facility. Design information was presented in two dimensional drawings with limited three dimensional perspective and scale models. The design models illustrated form of the proposed structure, but could not economically simulate either the construction process or truly represent materials or finishes. Similarly, production schedules (CPM, PERT Gantt) could only represent interactions between events over time, but were difficult to understand by the uneducated viewer. These traditional practices and graphic presentation tools do not facilitate the development of prototypes for evaluation and modification before the project is executed.

Available technology in computer graphics and interaction can simulate the entire building system life-cycle. The design data base (CAD) combined with a computer simulator similar to Bechtel's "WALKTHRU" process (discussed in Section 4.3) can allow the designer, consumer or producer to position himself/herself within any part of the system. With a systems like the Visual Scheduling Simulation System (VSS) the processes can be simulated by integrating the time element into the simulated model. The VSS system integrates project activity durations, imported from an outside CPM scheduling system, to a three dimensional computer (CAD) model of the project, this information is then translated via "WALKTHRU"

into a time-phase representation of the construction process."[11] Similar simulation processes could be used to represent and evaluate design alternatives and operational requirements; conduct trade-off analysis between component choices or changes; identify conflicts between spatial requirements over time; and perform value engineering of all components or alternatives before earth is turned.

Review of alternatives at any life-cycle stage or configuration would significantly reduce the cost and frequency of physical changes to the building system. This same information interaction of the building system could then be used to generate the documentation required to execute the erection of the structure as well as control the process of delivering the final product.

7.2 *TLC* INFORMATION INTERFACE

The information interface (Figure 21) represents the interaction of the key project specific information inputs and the standard data base libraries which contribute to the development of the system's working files. The system's working files consist of the five major information applications that represent the life-cycle phases of the final

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[11] Skolnick, Morad and Beliveau, page 335.

system; the Facility Program, the Design, the Production, the Logistics Support Analysis (LSA) and the Life-Cycle Cost (LCC). These working files process and transfer information based on object oriented data. When this data is processed or manipulated, not only is the prototype of the building simulated, but required construction documents generated and physical process control initiated.

7.2.1 Information Input

The information used to develop the *TLC* information interface is derived from two types of sources; project specific information, standardized data base "libraries" and application tools. Together these sources are manipulated within the project's working files to develop the specific profile of the project. In Figure 21, the project specific data inputs are represented by circles, while the standardized "libraries" are represented by the can shapes and application tools are represented by diamond shapes.

Information specific to the project is derived from an interaction between the *TLC* system and the participants (the designer, the producer and the consumer). The consumer's operational and functional requirements for the project are determined as well as the maintenance concept for the life-cycle support of the facility. Initial budget information is processed for the project including sources of financing,

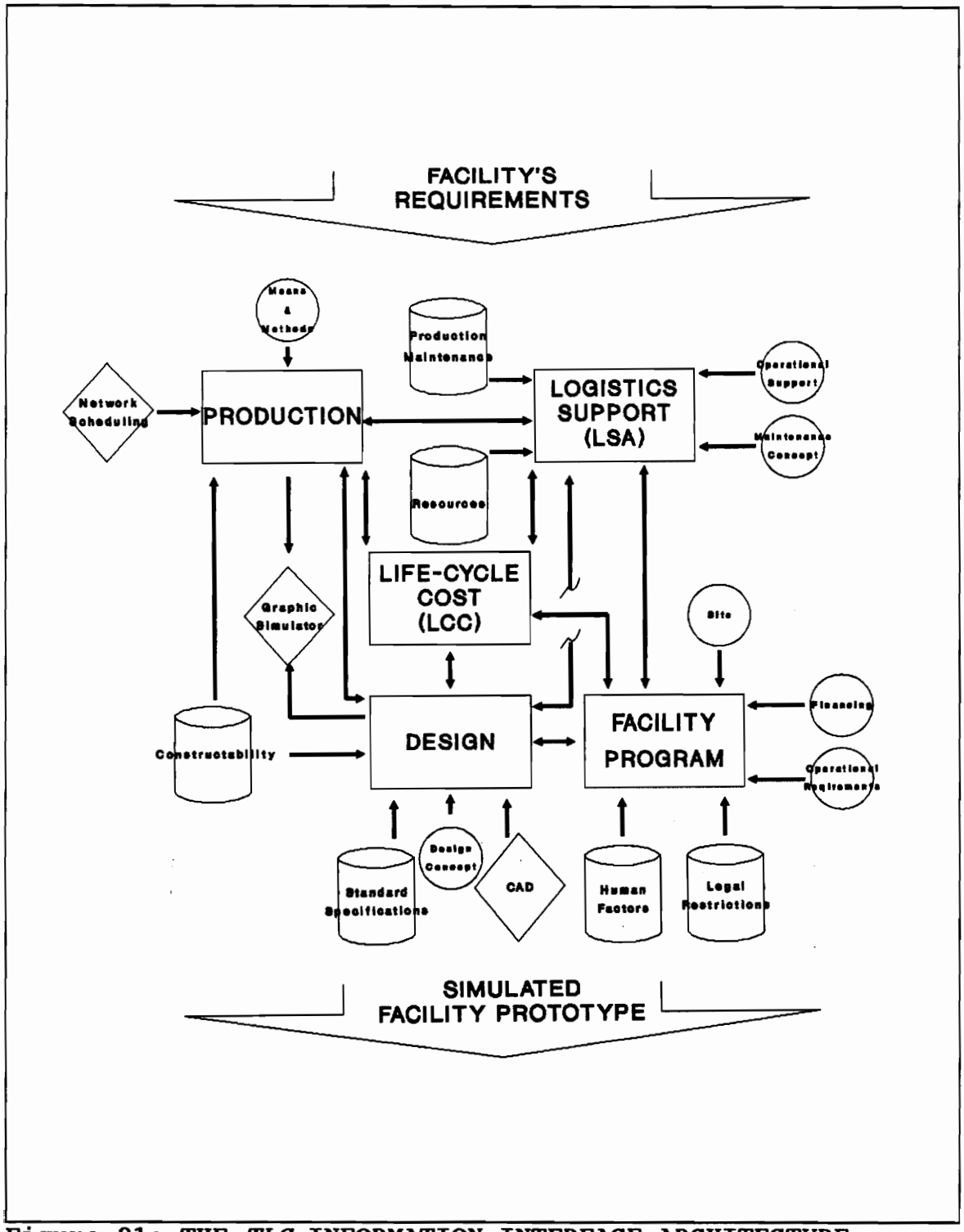

Figure 21: THE *TLC* INFORMATION INTERFACE ARCHITECTURE

required rate of return information as well as other economic considerations which will impact the life-cycle cost of the system. The designer inputs the facility's design concept, and the producer inputs project specific means and methods inputs (crews, equipment, site conditions, etc). All of these inputs to the system are continually monitored and updated as necessary during the design development and production of the facility.

The standard data base "libraries" will be made up of information which is not project specific and can be carried over from project to project. These "libraries" provide input to and analysis of alternatives based on project non-specific data which is updated when standards, methods or materials change. "Libraries" will include building code restrictions, resource production and source information, standard specifications and a constructability review. As an example, the constructability "library" will review the design and schedule for logical progression and application of means and methods of production.

Incorporated into the system will be application tools and software required to produce the interface, the CAD system, the network scheduling system, the graphic simulator, the data base management system, etc. Together with the knowledge based "libraries" and project specific data, these

tools provide the information sources and can be used to develop and evaluate the project working files developed for the facility.

7.2.2 Facility Program

The Facility Program file is envisioned to be similar to the building program currently used to determine requirements in the early phases of the design process. Simply stated, the Facility Program is the facility's specific requirements document. The Facility Program translate the consumer's needs, support requirements and legal restrictions into a single source file to be altered and modified by the consumer and designer to establish the project's baseline requirements.

The Facility Program translates the consumer's requirements into a feasible preliminary organization of building functions. The functional requirements, maintenance concept and support plan of the facility are merged with legal restrictions (building codes, zoning), site conditions (physical parameters and environmental conditions) and human factors considerations (access, comfort, light, noise, etc) to develop a picture of the facility's requirements and restrictions. These attributes are then balanced with the initial budget of the project to provide the designer with an accurate representation of the consumer's needs.

The Facility Program will retain the logic information

that developed a specific requirement. Through this process later facility modifications which affect an element required by the program can be evaluated. If it is a "soft" or changeable requirement it will be altered to allow the modification. If it is a "hard" requirement, an element beyond the control of the facility designer, consumer or producer, the later decision must be altered. As the design progresses, these Facility Program requirements will be linked to design objects so future modifications of objects will be evaluated and designed against the same criteria. The Facility Program continually interacts with the other working files to eliminate conflicts between the working files as they relate to specific design objects.

7.2.3 Design

The Design working file merges the designer's concept for the facility with the requirements and restrictions developed in the Facility Program. The designer utilizes standardized specifications, CAD applications and parametric design capabilities to rapidly develop design alternatives. These alternatives can be evaluated against both the working files (Life-cycle Cost, Logistics Support, Production and Facility Program), as well as standard "libraries". "Hard" requirements from either source can be immediately incorporated into the design alternatives.

Specific design inputs and evaluations occur similarly for the facility's structural concept, mechanical systems, electrical systems and architectural considerations. The design process associated with these subsystems of the facility concept can be input by separate designers and merged within the design working file. The evaluation of the overall proposed design can then be processed for production through the production working file. Just as with the Facility Program, design logic and requirements are coded to specific three dimensional objects to facilitate evaluation of future modifications.

7.2.4 Production

The Production working file is a methodology to meld design requirements with the producer's means and methods of production. The design plans and specification are translated into an executable construction schedule. This schedule incorporates not only production activities, but with the inclusion of resource and maintenance considerations, an accurate picture of the time and monetary costs of facility delivery can be developed.

Once the producer determines the means and methods necessary to deliver the facilities with the manpower and equipment at his/her disposal, a delivery concept can be developed. The process is scheduled using a network

scheduling package (or other more advanced scheduling techniques) and resource considerations of materials and equipment maintenance delays are applied to the plan. The materials requirements from the design data base can be scheduled, ordered and controlled to optimize the inventory requirements. Equipment optimization and control can be evaluated in terms of both usage and maintenance requirements. After a constructability review and the incorporation of quality and cost controls, an accurate plan of attack for the delivery of the facility can be determined, and this plan can then be incorporated into production control.

7.2.5 Logistic Support Analysis (LSA)

Currently, life-cycle logistic support considerations are not formally incorporated into either the programing, design or production phases of the facility. Overhead costs of material inventory, project support and equipment maintenance are difficult to apply into current estimating and bidding practices. The long term costs of facility maintenance and utility costs are only cursorily applied to design considerations. *TLC* addresses these shortfalls with the incorporation of a formal Logistic Support Analysis (LSA).

The LSA addresses such things as component reliability, the facility maintenance cost, operational utility costs and the logistics requirements associated with the materials and

equipments required for production. The LSA performs two key functions in the information network, it identifies life-cycle support requirements and it assures the facility and production plan are designed for supportability.

Logistic support requirements for manpower, materials and support equipment are integrated into the design alternative. Through interaction with the Facility Program and the Production working files, logistic support requirements are identified and programed. Logistics and maintenance requirements during both production (construction) and operation can be evaluated. Impacts of design modifications on logistics acquisition and maintenance are coded to the object oriented design.

The logistics support in terms of material inventory, maintenance and utilities during both production and operation of the facility represents the largest portion of the project's life-cycle costs. By early identification and incorporation of these considerations in all aspects of the design and delivery of the system, *TLC* can significantly impact the cost and consumer satisfaction with the final product.

7.2.6 Life-cycle Cost (LCC)

The interaction of the design, production and LSA working files with the budgetary considerations of the project are

used to develop the facilities Life-cycle cost model (LCC). In terms of systems dynamics, the LCC represents the information network's level function. The element which reflects the systems status at a given time and is affected by and in turns acts upon other systems inputs and status."[11] The LCC is in itself a system network reflecting the cost inputs from the design, production and LSA considerations. Since the construction industry is a business, the LCC is used in the evaluation of each alternative at each phase of development.

As discussed in Chapter 3, the ability of a construction organization to financially manage its projects is a critical component in its profitability and potential for success. In its simplest terms, financial management is the ability to recognize and control the payment and receipt of capital. LCC is the *TLC* activity which allows the capital monitoring and control of a project's life-cycle cost commitment. But the cash-flows of a building system, are themselves a complex time-dependent system. The exchange of capital must occur within the economic environment, and is most significantly affected by the timing of the exchange. These three major components (time, capital exchange and economic environment) form the triad which creates and affects a facility's life-

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[11]Drew and Hsieh, page 458.

cycle cash-flow (Figure 22).

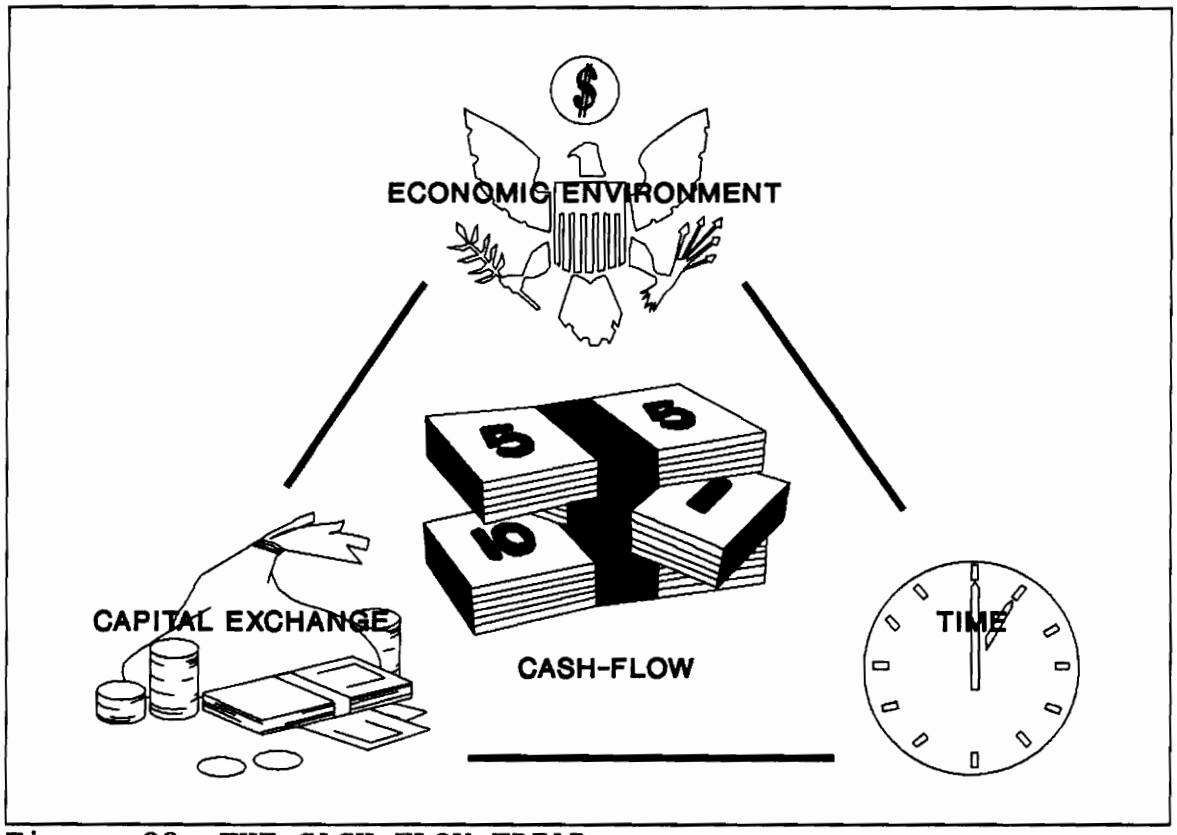

Figure 22: THE CASH-FLOW TRIAD

The economic environment forms the global conditions under which the facility must operate and determines the time-value of capital. Successful cash-flow management must incorporate the effects of inflation and local market conditions. The capital exchange of a construction project, as with any business, is the balancing of costs with payments. "The failure to recognize properly all elements of cost is one of the primary causes of trouble in the construction

industry."[100] The project's useful life-cycle imposes the major time impact on the facility's cash-flow network. All expenditures and payments for design production and operation are integrally tied to the life expectancy of the project.

TLC will facilitate the development of both accurate budgets and cost control processes. Information transfers regarding the elements of the cash-flow triad will be obtained within all working files of *TLC* and processed by the LCC model. Cost considerations coded to design objects will highlight the cost of current configurations and later modifications. Cost tradeoff analysis will be immediately incorporated into any design alternative or proposed change. This LCC information can then be used to guide other developments and evaluate design alternatives.

7.2.7 Information Flow

By referring again to Information Interface Architecture (Figure 21, repeated in Figure 23) the flow of information between the elements during a project can be illustrated. This discussion will follow a linear progression similar to the generally accepted life-cycle of a facility design. As mentioned previously however, the process is not linear, an interactive, time sensitive, exchange of processes information

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[100]Park, William R, Construction Bidding for Profit, (New York, NY: John Wiley and Sons, 1979), page 108.

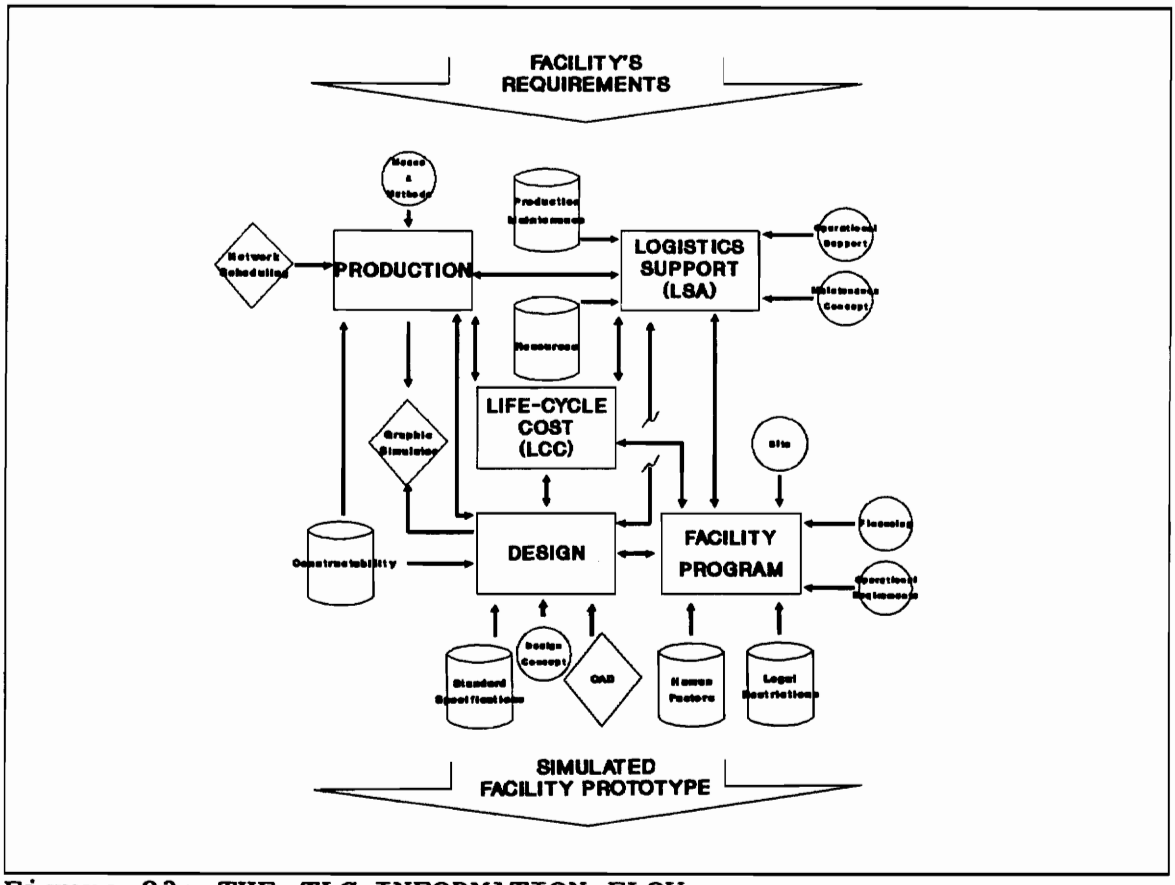

Figure 23: THE *TLC* INFORMATION FLOW

between elements.

The process discussion will commence at the Facility Program file. The Facility program develops the requirements documentation used in other stages to develop and analyze alternatives. The Facilities Program receives data from two types of sources project specific and project non-specific files. It also receive processed information from the Logistics Support Analysis (LSA) and the Life-cycle Cost (LCC) files. The project specific data is related to the financing

restrictions, the site or environmental restrictions and the operational requirements of the facility. All of this data is derived from the owner and/or operator of the facility. The project non-specific data (the "library" data) includes basic human factors requirements (safety, anthropometric data, etc) and legal restrictions (zoning, access, etc). The data is processed into information which represents the basic requirements of the facility.

The Design file receives this information as well as inputs from other sources to develop alternative solutions. Other data inputs include the project specific design concept and non-specific "library" inputs analysis from the constructability review and the standard specifications file. This data is combined with the requirements information from the Facility Program and LCC files. The Design file processes the input data into a proposed design which is forwarded to the Production file as well as the graphics simulator.

The Production file processes the proposed design into a proposed building sequence. The Production file receives additional inputs from the project specific materials and methods determinations of the producer, the non-specific constructability review, and the network scheduling software. The Production file also interacts with the LSA for information or production resources and with the LCC for cost

implications of alternatives. The Production file can then communicate back to the Design file if alternative design solutions are required.

The Logistics Support Analysis (LSA) file processes project specific data on the facility maintenance concept and operational support requirements and project non-specific data on resources (both production and operational) and production maintenance requirements. The LSA interacts with information from the Production, Design Facility Program and LCC files to evaluated and update alternatives for supportability.

The Life-cycle Cost (LCC) file interacts with all other files to evaluate and optimize the cost alternatives. None of the files is an independent activities, but requires the input processes information and evaluation mechanisms of the other files. The *TLC* information flow is not static or linear. It is an iterative process which can evaluate alternative and yield a time sensitive representation of the alternative (through the graphics simulator). The simulated facility prototype can be viewed, altered and optimized as the design is developed.

7.3 *TLC* IN OPERATION

The delivery of building systems in the twenty-first

century will be a fully automated process controlled by a single operator at a terminal similar to those used by today's air traffic controllers.[101] The operator will control output and schedule through the synthesis of the design and schedule data bases and feeding this information to the microprocessors serving regular system users and controlling each robot or piece of equipment. Position and productivity information will be transmitted back to the controller from both fixed on-site and equipment-mounted sensors.[102] The users or operator can then control equipment operations by interfacing control interaction with the *TLC* design and schedule working files.

To make this view of the future possible, the *TLC* information interface must be able to process and incorporate many of the independent actions of the design and production functions. *TLC* is not a linear process. The traditional approach to the design, development, delivery and operation of a building systems is a linear progression from design professional(s) through constructor(s) to operator. The operational requirements of maintenance and support are almost totally ignored by the designer and producer. *TLC* will yield,

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[101]Bechtel Media Services, Constructs 2000.

[102]Beliveau, Yvan J, "Position and CAD data Integration for Improved Project Control", Journal of Transportation Engineering, Volume 116, Number 6, (New York, NY: ASCE, November/December 1990), pages 4-6.

through interaction of both information and industry participant, a true parametric design process. Users requirements are input to the system and are processed into a final designed facility ready for execution.

TLC is an iterative approach to design production and operation. To avoid or eliminate the communication pitfalls between the disciplines and participants in the process, *TLC* utilizes an interactive network requiring interaction and feedback between both participants and life-cycle phases. Because of this interaction and the simulated model of the life-cycle of the facility, *TLC* can produce the design documents derived from its information interface. Just as significantly with increased technological advances, *TLC* can be used as the information source to physically control production activities.

Information dissemination is the key to success of any undertaking. *TLC* will enable the information processed and simulated within the information interface to be transmitted (physically or electronically) to the person who requires it and just as importantly in the detail required. Figure 24 represents the two basic types of information formats disseminated from *TLC*, Process control and documented data.

7.3.1 *TLC* Data Documents

During the design process, *TLC*'s ability to simulate all

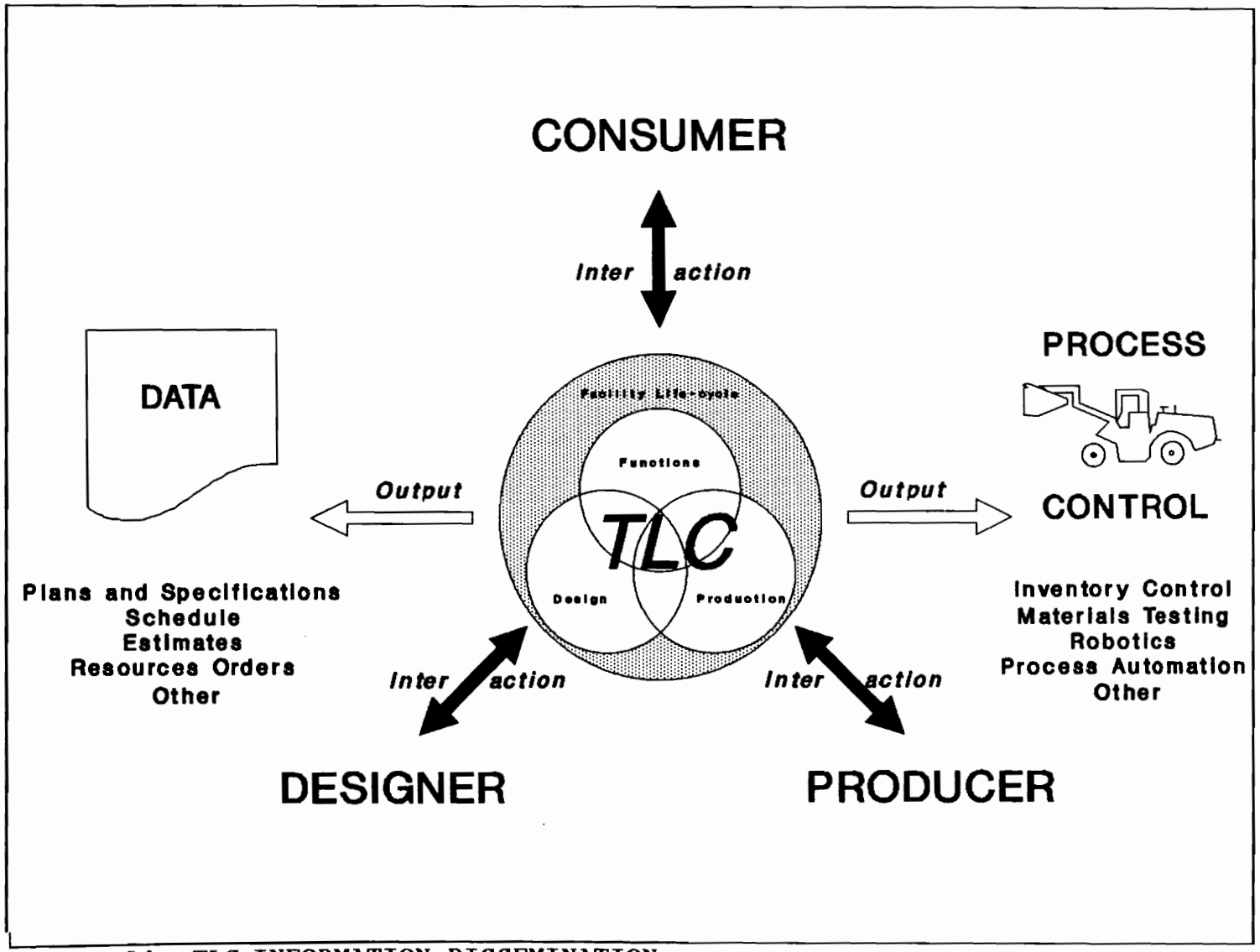

Figure 24: *TLC* INFORMATION DISSEMINATION

aspects of design alternative to include production and operational issues will greatly advance the incorporation of life-cycle logistics and cost concerns in each design alternative. Through the integration of the object oriented working files with a three dimensional graphic animator, all aspects of the proposed facility can be visualized over time. The impacts of changes or design alternative can be readily visualized as the facility is simulated through time. Following evaluation and optimization of the design, documentation required for the execution of all aspects of the process can be generated and transferred to the required user. These document files can be either hardcopy or electronic or both.

The *TLC* information network will be able to both simulate and document all aspects and phases of the facility's design process, production cycle and operational requirements. Standard construction documents (plans, project specifications and schedules) can be produced and transferred to the user in both a timely and accurate manner. Revisions, modifications and information coordination of such documents will become a significantly simpler process. Direct interface with resource libraries and suppliers will allow for a move towards the "just in time" order and receipt of support materials for reduced inventory and overhead, both for facility production

and operation.

The current communications and conflict problems experienced both across disciplinary and educational level can be reduced or eliminated. The consulting structural, mechanical or electrical engineer of today becomes an input into the design working file which automatically optimizes spatial conflicts and reviews the design for both constructability and conformance to specifications and requirements. As this information is merged and finalized, it can be reduced or expanded to suit the target user of the data; as vague as a wiring schematic or as specific as a structural steel rivetting pattern. Shop drawings from fabricators are similarly input and reviewed for conformance and accuracy. Changes are immediately identified and adjustments incorporated as necessary. The final outputs are flexible documents and files which are accurate, timely and in sufficient detail to meet needs.

7.3.2 Process Control

Since *TLC* will simulate all aspects and phases of the facility's life-cycle, its generated information interface can also be used to produce both control plans and to control equipment and physical actions. The interaction of the three dimensional drawings and the time schedule of actions will enable the production planner to place planned objects,

materials and equipment at specific points in time and space. Through sensors and feedback control, the progress of these positions over time can be monitored and modified as necessary.

The development of quality control, production control and cost control plans will parallel the development of design alternatives. The control of inventory, equipment and activities during production will then be a matter of comparing existing time-space conditions to planned conditions. Interfaces with electronic positioning and digital photometry information sources can provide accurate comparisons of on-going and completed work with the planned structure for evaluation of productivity and schedule adherence. Quality control and materials testing can become an on-going automated testing process, with termination of activities if tolerances are not met.

Robotics will be increasingly used within the construction industry. Robots will become readily excepted for toxic or repetitive jobs in construction just as they have been in manufacturing. Bar code information on materials received will enable automated storage and retrieval of resources in the same manner as this process is being used

today in the manufacturing industry.[103] With enhanced positioning control and accurate three dimensional data bases, robots will be able to serve an increasing role in repetitive erection and finishing activities in hostile or restrictive environments.[104] With the *TLC* standard information base and information transfer, all robotic construction activities become feasible.

Control is the ability to "check, regulate, restrain, dominate or command"[105] an activity. Information is the key to control. *TLC* will provide and information data base of sufficient detail to both ease communication and enhance control. With a common information source, development and interaction between design and execution can become a unified effort reducing both conflicts and a facility's life-cycle costs.

7.4 SUMMARY

This chapter has proposed the architecture for the

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[103]Seifert, Laurence, "Design and Analysis of Integrated Electronics Manufacturing Systems", Design and Analysis of Integrated Manufacturing Systems, (Washington, DC: National Academy Press, 1988), pages 15-16.

[104]Hendrickson and Au, page 485.

[105]ELIA, page 221.

information interface required for *TLC*. This architecture employs current facility design and production requirement with the life-cycle cost and logistics concerns of Systems Engineering to produce a theoretical information management system. This object oriented system can be used for the parametric design of facilities; the evaluation and reduction of facility modifications; and, when combined with other systems, control the production and operation of the facility.

TLC will provide an information network and production control mechanism which will enable the delivery of facilities which incorporate all life-cycle requirements. The ability to rapidly evaluate and simulate complete life-cycle design alternative early in the developmental process will reduce the necessity of costly changes during production. The ability to accurately illustrate time and space relationships will enable increased automation and enhanced control over the production of facilities. A common approach to the required reference data base for the automated construction site of the twenty-first century will enable increased development of robotic and computer controlled processes with less repetition of effort and at reduced costs.

VIII. SUMMARY, RECOMMENDATIONS AND CONCLUSIONS

"New opinions are always suspect, and usually opposed, without any other reason but because they are not already common."

- John Locke[106]

The future is now. The construction industry must respond to the economic and professional challenges facing it. One conceivable method to face these challenges is to modify traditional organizational approaches to facility development and delivery with life-cycle considerations and computer based communication interfaces *Total Life-cycle Construction (TLC)*. *TLC* will provide the framework for the information and control system needed to develop the futuristic construction industry only fantasized of by authors and dreamers like H G Wells, Jules Verne, Isaac Asimov and Ray Bradbury decades ago; robotic construction tools building the structure and cities of the twenty-first century in either normal or hostile environments, under the seas and in the heavens.

8.1 PROJECT AND REPORT SUMMARY

This project and report has explored the current status

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[106]ALIA, page BT-67.

of the construction industry in terms of organization, tools and in financial terms. The problems identified as well as the process requirements were then translated through the principles of Systems Engineering into a requirement for a new means of information management. Since communication and the ability to manage change can be traced as the prime causes of problems today, the *TLC* system uses the reduction of these challenges as its premise.

TLC is a hybrid od current approaches to the design and delivery of operationally satisfying facilities. The communications problems of the past can be significantly reduced; facilities will become more economical in operation and design; construction processes can be streamlined; and, the ability to incorporate computer control and robotics within facility production could be fostered via a common information data base. Just as the Master Builder of the past and the design-construct firms of today, the *TLC* operation of tomorrow will rapidly respond to the consumer's needs with a fixed line of both responsibility and liability.

8.2 *TLC* APPLICATION

The *TLC* approach to facility design and development can begin today, even before technology is developed. As much as

anything, *TLC* is a philosophy which exploits the benefits of information transfer and feedback. The needs, requirements and restrictions of a project are fully identified, refined and continually updated. Decisions, changes and modifications are considered and evaluated early in the system's life-cycle to maximize their effectiveness and minimize their financial impact. Information is shared by and sought from each participant (consumer, design and producer) in the process at each stage to optimize the solutions and minimize the conflicts and requirement for later change. This basic life-cycle approach and philosophy has not been fully implemented in the past to complexity and fragmentation of the construction industry. Today technology exists to ease or eliminate the conflict between disciplines.

The basic microcomputer technology required to create the twenty-first century construction industry is present today or being rapidly investigated. The process of linking the information and available technologies requires a framework for development. Developmental efforts of government agencies, universities and the industry itself are making the dreamers' dreams a reality. Technical innovation of the past were based on the automation of human action, the *TLC* approach develops the information interfaces and process control on facility and production functional requirements, rather than

simply automating or computerizing existing operations. The intended scope of *TLC* will require the interaction and development of several research possibilities.

8.3 FUTURE RESEARCH

The possibilities for research in the development of the construction industry of the twenty-first century are numerous. A current restriction or complication to these developments is the lack of a common focus and standard data base. *TLC* can provide this needed baseline. In addition to the development of the data interaction of the *TLC* network itself, a multitude of other opportunities exist (Figure 25).

TLC research activities can be divided into two basic categories; information management and process control. Information management encompasses the development of the information interfaces, the development of the knowledge-based data "libraries" and the development of optimization and management tools. The LSA and LCC model development and interface into *TLC* will represent the most significant change in the direction of construction management. These systems engineering principle (typically included in the manufacturing industry) have rarely been fully integrated into the construction process.

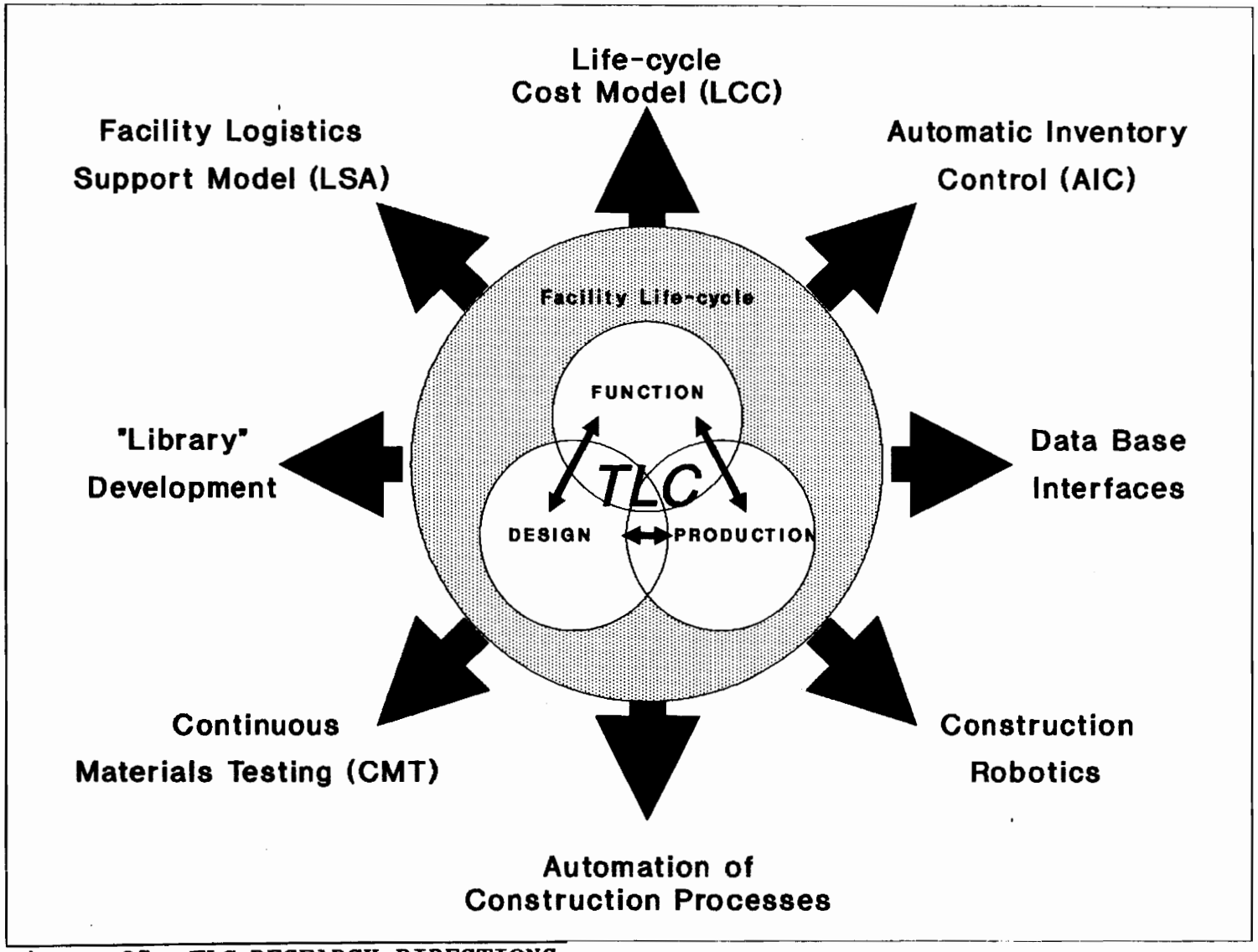

Figure 25: *TLC* RESEARCH DIRECTIONS

In the arena of developmental control, *TLC* can provide the "common ground" for advancement in research to control the physical process of facility erection. By creating a standard data reference format, control applications can focus on physical requirements instead of process intelligence. With a standard for process and design simulation information, control applications can be developed with reduced developmental and implementation costs for producers in the future. Process control applications, robots and computer controlled equipment become the drill bit of the future, while *TLC* serves as the drill.

8.4 CONCLUSIONS

By combining information transfer and process control through a network conceived and designed with facility life-cycle implications in mind, *TLC* can chart the way into the construction industry of the twenty-first century. *TLC* can avoid the process turmoil caused by the complex, specialized multidisciplinary nature of the construction industry. Timely transmission and feedback of information, improved process control, and complete consideration of logistics and operational requirements of the facility are earmarks of this system.

The construction industry of the next century will bear little resemblance to organizations of the past either technically or professionally. The technical advance of the *machine age* and the *computer age* will mandate a change. The slow evolutionary practices of the past will not adequately support this change. The construction industry can not merely automate current practices and relationships. A revised approach to organization and operation is needed, the life-cycle principles of systems engineering can yield a road sign in this developmental crossroads.

Concepts and applications like *TLC* will make design a dynamic and on-going process within a facility's life-cycle. Design documentation will become a data file transfer to the consumer, unlike the current drawings which remain the property of the architect. The consumer will use this same data for operational and maintenance control of the facility as well as future modifications. The designer and producer will replace today's architect and contractor as co-equal professionals. Competitive bidding, a major hazard in today's construction industry will become irrelevant as facility's costs are viewed as total life-cycle operations, not fragmented design, delivery and operational phases.

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VITA

Roger Alan Hein was born on August 13, 1959 in Fergus Falls, Minnesota. He graduated from T C Williams High School, Alexandria, Virginia in 1977. He completed his undergraduate studies in Architecture at North Dakota State University, receiving a Bachelor of Arts in Architectural Studies in 1981 and a Bachelor of Architecture in 1982. After being commissioned in the United States Army Corps of Engineers, he entered active military service in 1982.

Within the military, he has served in both the United States and Europe, supervising military engineer personnel as well as designing and controlling minor military construction. In August 1989, he began graduate studies at Virginia Polytechnic Institute and State University in Systems Engineering concentrating in Construction Management under a military funded program of study. The major focus of graduate studies has been in the areas of construction liability and the applications of Systems Engineering principles to the construction process. Following graduate program completion, the author is being assigned to the Defense Intelligence Agency to supervise the design and acquisition of military computer systems.

GRADUATE PROGRAM OF STUDY

SYSTEMS ENGINEERING:

ENGR 5004 - The Systems Engineering Process (Fall 1989)
ENGR 5104 - Applied Systems Engineering (Spring 1990)
ENGR 5904 - Project and Report (Fall 1990)

CIVIL ENGINEERING:

CE 5014 - Construction Control Techniques (Fall 1989)
CE 5024 - Contract Administration and Claims Resolution (Spring 1990)
CE 5974 - Engineer Professional Liability (Summer 1990)
CE 5034 - Construction System Design and Integration (Fall 1990)
CE 4034 - Construction Specifications (Spring 1990)
CE 4804 - Professional and Legal Problems in Engineering (Summer 1990)

INDUSTRIAL ENGINEERING AND OPERATIONS RESEARCH:

IEOR 5434 - Economic Evaluation of Industrial Projects (Fall 1989)
IEOR 5204 - Manufacturing Systems Engineering (Fall 1989)
IEOR 4614 - System Safety Analysis (Fall 1990)
IEOR 4424 - Logistics Engineering (Fall 1990)
IEOR 3614 - Human Factors Engineering (Summer 1990)

NON-ENGINEERING:

MGT 5304 - Social, Legal and Ethical Environment of Business (Spring 1990)
FIN 5014 - Commercial Law (Spring 1990)