



A MODEL PROCESS FOR MAINTAINABILITY IMPLEMENTATION

by

Jeffrey S. Russell
Professor

John R. Meier
Graduate Research Assistant

and

Blia Moua
Graduate Research Assistant

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EXECUTIVE SUMMARY

Faced with shrinking maintenance budgets and increasingly competitive markets, maintainability is an issue of growing importance for many companies. Although, maintainability is not a “new” concept, many companies struggle with consistent, standardized maintenance input during the project delivery process. An important characteristic of any design, maintainability pertains to the ease, accuracy, safety, and economy in the performance of maintenance actions. This research examines the opportunities available through the effective inclusion of maintainability concepts during the project delivery process.

The Construction Industry Institute (CII) defines maintainability as the optimum use of facility maintenance knowledge and experience in the design/engineering of a facility that meets project objectives (Constructability Implementation Guide 1993). In this context, maintainability refers to a formal process to include relevant maintenance input during all phases of the facility delivery process. The Maintainability Research Team adopted a format similar to constructability for its research methodology and developed model process.

Research Purpose and Objectives - The primary purpose of this research is to develop a model process for incorporating maintenance knowledge and experience into the planning, design, procurement, construction, and start-up of facilities. Specific research objectives include: (1) define existing levels of maintainability implementation; (2) identify best practices that improve maintainability of capital projects; (3) compile a model process for implementing maintainability; and (4) conduct case studies to illustrate best practices and the model process for maintainability implementation.

Research Scope - Given complexity and variations of maintainability, this research focused on general practices to aid in formalization of maintainability efforts during the project

delivery process. Formal implementation of maintainability is not sufficiently mature to obtain quantitative data, and it would be difficult to develop a basis for evaluation. The scope of this investigation is limited to maintainability activities during six phases of the project delivery process: (1) planning; (2) design; (3) procurement; (4) construction; (5) start-up; and (6) operations and maintenance. This research surveyed a broad cross-section of companies engaged in many different types of construction, ranging from general building to petrochemical. Capital and retrofit projects for equipment, systems, and facilities were included in this research. As maintainability most directly impacts the owner of constructed projects, this research focused on owner organizations.

Research Methodology - The research methodology included: (1) literature review; (2) a questionnaire survey; (3) 35 personal and telephone interviews; and (4) seven in-depth case studies with industry representatives.

Levels of Maintainability Implementation - The research data revealed attributes that were subjectively organized into five levels of maintainability implementation: (1) design/engineering experience; (2) effective organizational standards; (3) developing maintainability process; (4) formal maintainability process; and (5) comprehensive maintainability program. Each level expands and refines the attributes of the preceding level, increasing the opportunity for maintainability improvement on capital projects.

Model Process for Maintainability Implementation - Best practices observed during the research data collection were organized into a model process for maintainability implementation. The model process was developed to provide guidance in the planning, development, and implementation of maintainability at both the corporate and project levels. Providing an overview of the maintainability program, the model process has six milestones: (1)

commit to implementing maintainability; (2) establish maintainability program; (3) obtain maintainability capabilities; (4) plan maintainability implementation; (5) implement maintainability; and (6) update maintainability program. Each milestone contains several steps and activities that further describe the details of implementation.

Practical Applications – Project-specific factors affecting the need for maintainability efforts are grouped into two categories: owner related issues and project attributes. The owner related issues are: (1) owner type; (2) past maintenance experience; (3) maintenance strategy; and (4) projected cost of maintenance. Project attributes include: (1) construction type; (2) criticality; (3) complexity; (4) projected life of facility; and (5) location. Five factors that affect how a formal maintainability process will be implemented are: (1) new versus retrofit; (2) project size; (3) project delivery system; (4) maintenance organization; and (5) related industry practices.

Conclusions - Implementation of a formal maintainability process involves a fundamental shift in the role of maintenance, from a necessary “evil” to a value adding activity, in the project delivery process. Maintenance helps achieve and sustain optimum reliability and performance for all projects. Formal maintainability programs provide benefits to both owner and contractor organizations. Owners benefit from improved control over maintenance costs and improved facility availability. Designers and constructors can increase client satisfaction and use success with a maintainability process as a value-adding service for owner clients.

Recommendations - Each company must assess the need for maintainability on future projects and then determine the appropriate level of maintainability efforts. Development of the formal process should reflect the organizational need, with the purpose of ensuring maintainability objectives are met. A maintainability process has the potential for greatest (and

most cost effective) impact if it can be integrated with existing company work processes and related improvement initiatives, such as Total Quality Management, etc.

Need for Future Research - Future research needs to be conducted in measuring and quantifying costs/benefits of maintainability in order to demonstrate the financial aspects of maintainability. Similarly, the need exists to measure and document performance of the maintainability process implementation.

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CHAPTER ONE

INTRODUCTION

1.1 PROBLEM CONTEXT

Faced with shrinking maintenance budgets, fewer new capital projects, and increasingly competitive global markets, maintainability is a matter of growing importance for many companies. Owners expect and need new capital projects and renovations to be not only functional, but also maintainable and reliable. Maintainability pertains to “the ease, accuracy, safety, and economy in the performance of maintenance actions (Blanchard et al. 1995)”, and is an important characteristic of any design. Simply stated, maintainability is the ease of performing work needed to keep a product, system, or facility operating effectively.

Maintenance has often been viewed as a necessary evil, an afterthought that drives up operating costs while adding nominal value. Historically, capital cost, schedule, and functionality parameters receive emphasis during project design and construction. In many instances, less attention is given toward long-term design characteristics such as maintainability, reliability, operability, and human factors. As a consequence, lack of reliability and maintainability consideration during design often results in higher maintenance and support costs over the life of the project (Blanchard et al. 1995).

The true cost-effectiveness of a capital project is its performance and cost throughout its life cycle. Maintenance costs are a major part of the total operating costs of all constructed facilities. The Building Research Board recommends that 2 to 4% of building replacement asset value be allocated to maintenance each year. In the process and manufacturing industries, maintenance costs represent between 15% and 40% of the costs of

goods produced (Mobley 1990). Studies indicate that American industry spends more than \$200 billion each year on maintenance, and production losses due to equipment downtime usually equal or exceed maintenance costs (Fogel and Petersen 1997). Maintenance represents a significant area for cost improvement in the project delivery process.

Appropriate levels of maintainability seldom occur by chance. It requires upfront planning, objective setting, disciplined design implementation, and feedback from prior projects. A more structured and focused maintainability process benefits owner companies through lower maintenance costs and increased productivity (function or availability). It is the first step of an effective maintenance program, linking maintenance goals to the design process. Maintainability also benefits contractor organizations, which can expand their services to include maintainability in the design and construction of capital projects. Many engineering and construction companies recognize that today's customer requires more than only design and construction capabilities—they require a holistic, seamless, integrated cost-effective solution.

Maintainability is not a “new” concept, yet many companies struggle with consistent, standardized maintenance input during the project delivery process. Within many of these companies, independent efforts produce isolated pockets of success but lack consistency in their application and results. This research addresses these implementation issues by compiling industry best practices in maintainability and organizing them into a model process. Similar to constructability, the model process consists of six milestones that contain steps to address maintainability issues at both the corporate and project level.

1.2 EVOLUTION OF RESEARCH LEADING TO MAINTAINABILITY

The mission of the Construction Industry Institute (CII) is “to improve the safety, quality, schedule, and cost effectiveness of the capital investment process through research and implementation support for the purpose of providing competitive advantage to its members in the global marketplace.” Maintainability affects the quality and cost effectiveness of constructed projects over the entire life cycle. Planning, design, and construction for maintainability is the next phase of the evolution towards a seamless, integrated project delivery process. Prior CII research teams have studied the challenges and potential benefits of an integrated project delivery process. Figure 1.1 shows the chronological history of the research publications leading to this research project.

Constructability implementation, pre-project planning, and design for start-up all reflect the importance of timely input of relevant design and construction knowledge. Key issues within a given phase were identified and fed forward in the process, improving the cost effectiveness of capital investment. Pre-project planning focused on the importance of scope definition and addressing project issues at the early stages of the project. Figures 1.2a through 1.2e illustrates the traditional disconnect between project phases, and the expanding integration of phases proposed by these research projects.

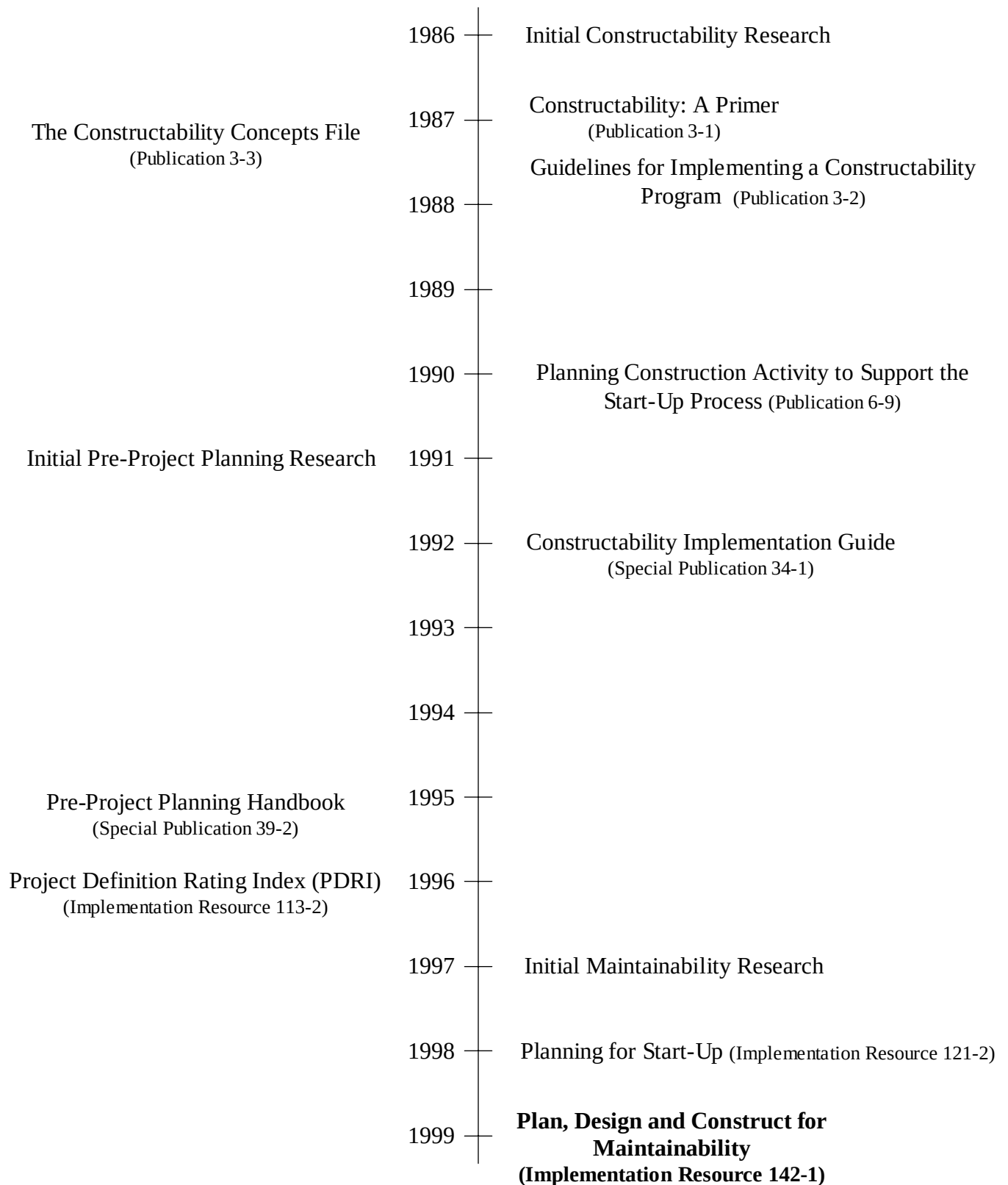


Figure 1.1: Chronological Listing of Prior CII Research Leading to Maintainability

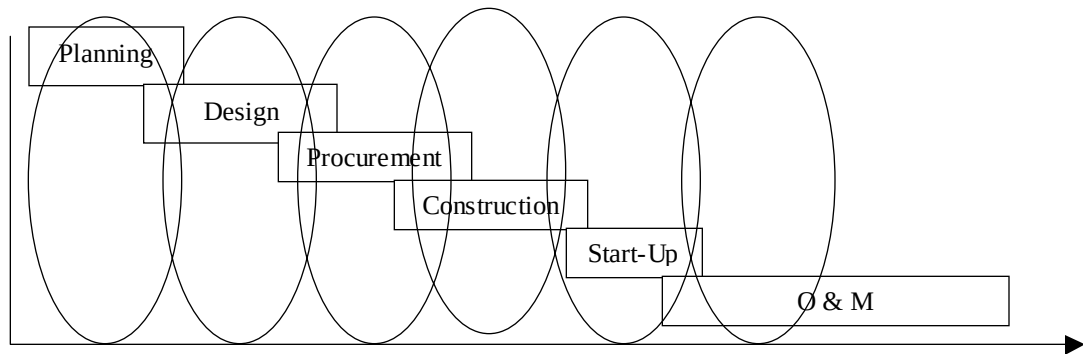


Figure 1.2a: Historical Disconnects (‘stovepipes’) Between Project Phases

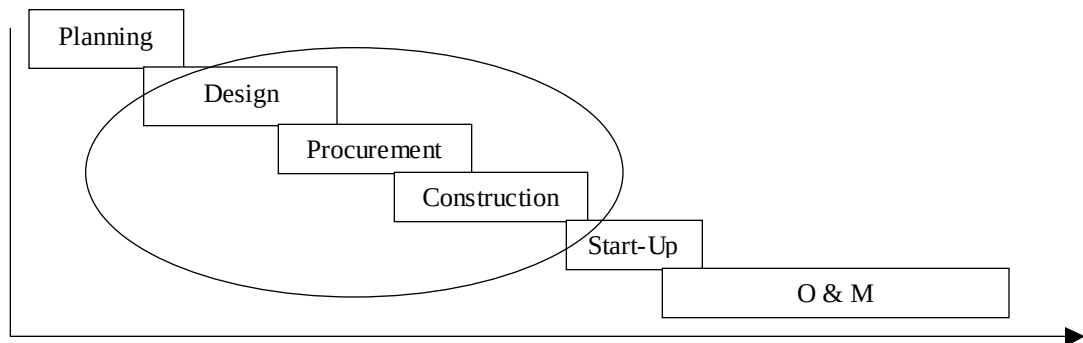


Figure 1.2b: Constructability Integrates Design and Construction

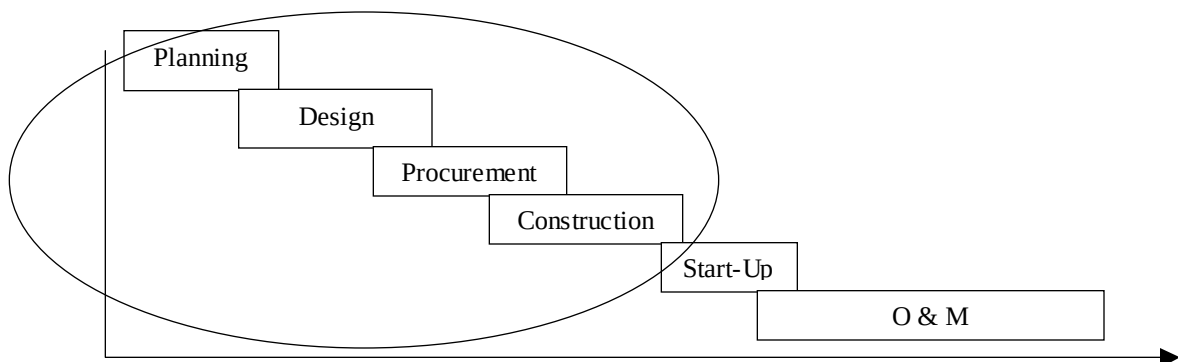


Figure 1.2c: Pre-Project Planning Addresses Critical Project Design and Construction Issues During Planning

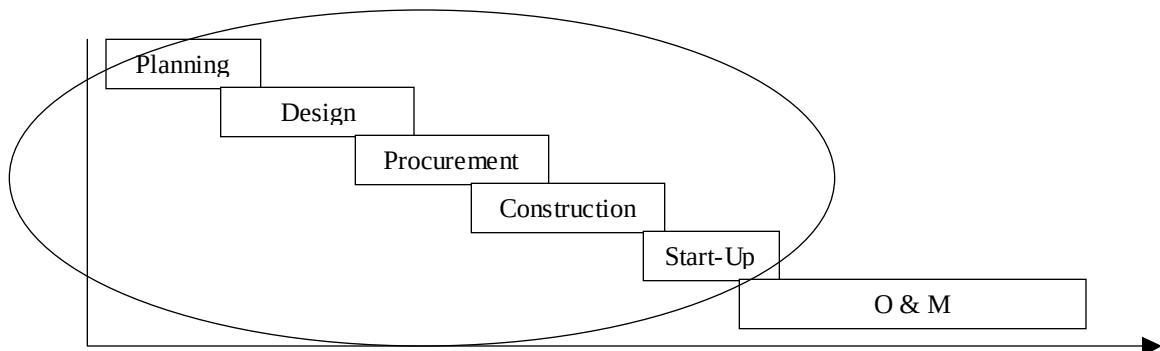


Figure 1.2d: Planning for Start-up Expands Integration

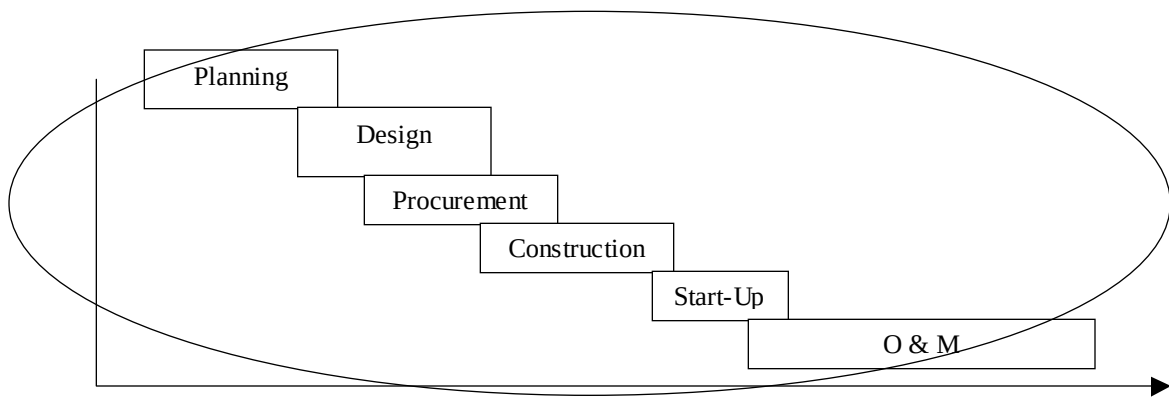


Figure 1.2e: Maintainability Completes Integration

1.3 INTEGRATED PROJECT DELIVERY PROCESS

The ability to influence project outcomes is greatest during the planning and design phases of the project delivery process, and maintainability knowledge and experience is most influential during these early phases. As shown in Figure 1.3, the ability to influence project outcomes decreases significantly with time. Maintenance requirements are largely fixed at the time of final project design. Maintainability improvements that are installed after contract award and project completion are more expensive and time consuming than if they were included in the original project design.

Historically, a maintenance program is developed as an afterthought, after systems have been chosen and installed. The ultimate goal of a maintenance program is to provide for high availability, whether it is mechanical systems in an office building or process equipment in a chemical plant. Many companies currently focus on improving maintenance programs of existing facilities through comprehensive maintenance strategies such as Reliability-Centered Maintenance (RCM) or Total Productive Maintenance (TPM), while providing less attention to new projects. However, each new project presents a unique opportunity to improve or enhance the maintainability. A capital project maintainability

process should be the first step of an effective maintenance program. Figure 1.4 illustrates the key elements of an effective maintenance program.

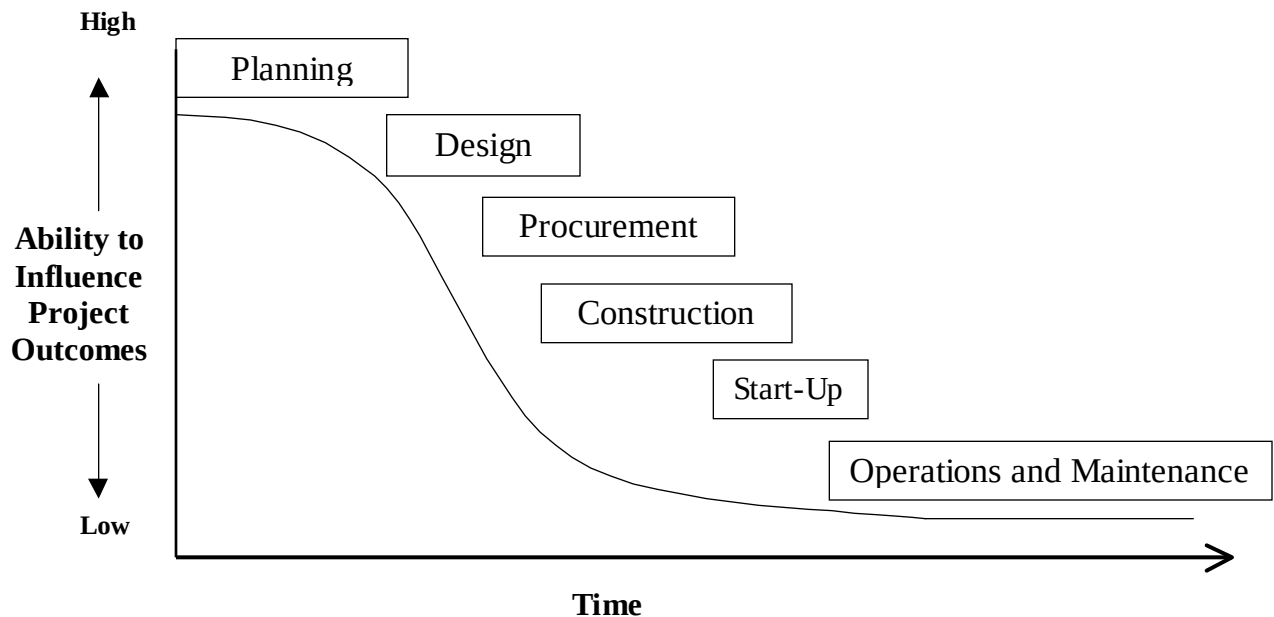


Figure 1.3: Ability to Influence Project Outcome over Project Life Cycle

(Source: “Constructability: A Primer” 1986)

Maintainability offers an additional method to improve return on capital investment. In “The Business Stake in Effective Project Systems,” the Business Roundtable describes the benefits of improving the project delivery process. The study contains data from over 2,000 projects from a variety of industries and represents over \$300 billion in total investment (“Business Stake” 1997). As shown by Figure 1.5, project delivery improvements enhance both cost and schedule, and also positively impact the operability of capital projects. Further research is needed to define the relationship between operability and maintainability, and to quantify the impact of project system improvements on maintainability.

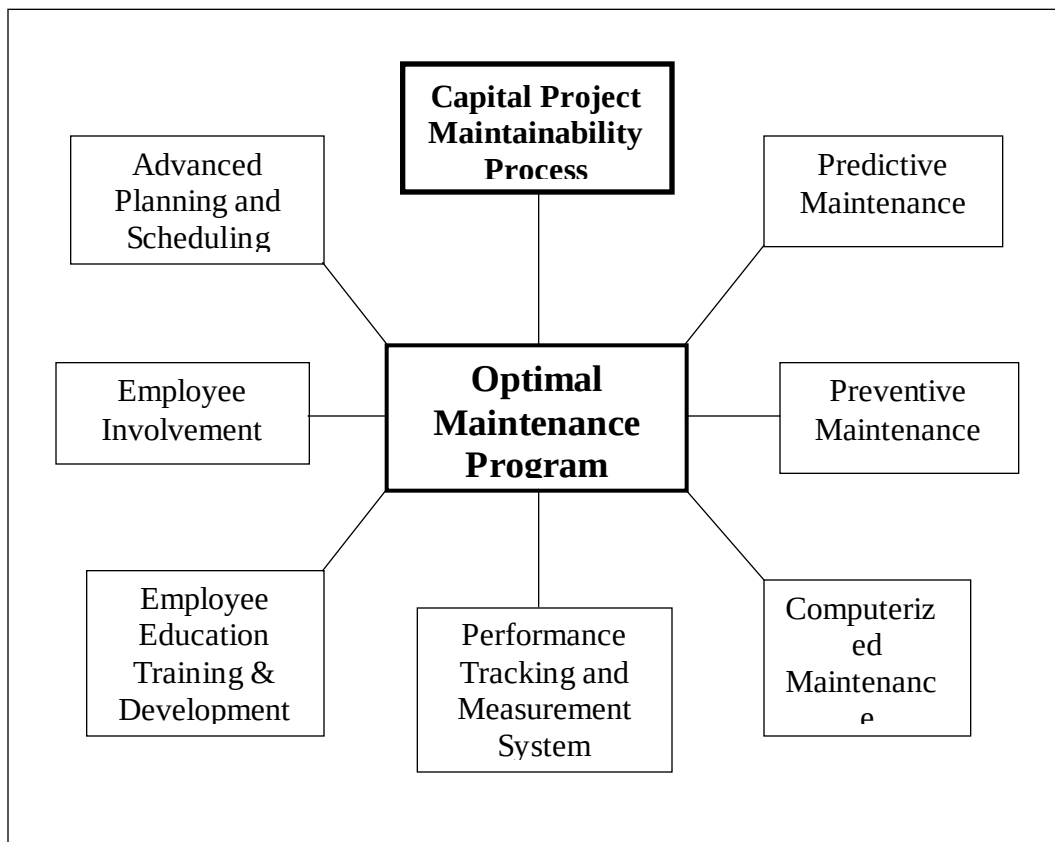


Figure 1.4: Elements of an Effective Maintenance Program
(adapted from “Developing a World-Class Maintenance Program” 1997)

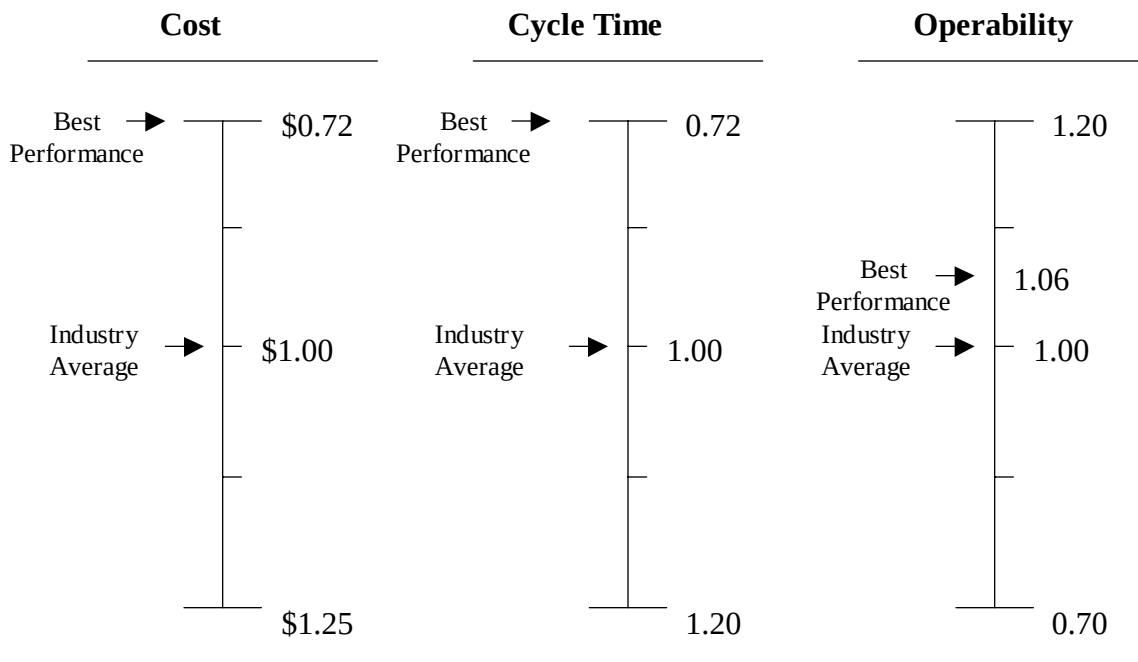


Figure 1.5: Benefits of an Improved Project Delivery Process
(“Business Stake” 1997)

1.4 RELATED INDUSTRY PRACTICES

Many of the activities and issues raised during a formal maintainability process are similar to activities of several existing corporate programs. A maintainability process has the potential for greatest (and most cost effective) impact if it can be integrated with existing company strengths. Understanding related maintainability practices helps define the role of maintainability and how to best implement a formal maintainability process within an organization. Figure 1.6 presents the general relationship of the major related industry practices, which are described below.

1.4.1 Quality Improvement

A maintainability program can be considered part of organization-wide Total Quality Management (TQM) efforts. The United States Department of Defense defines TQM as:

a strategy for continuously improving performance at every level, and in all areas of responsibility. It combines fundamental management techniques, existing improvement efforts, and specialized technical tools under a disciplined structure focused on continuously improving all processes. Improved performance is directed at satisfying such broad goals as cost, quality, schedule, and mission need and suitability. Increasing user satisfaction is the overriding objective.

Maintainability is one of several factors contributing to a quality project. Quality is “the totality of features and characteristics of a product or service (or process or project) that bear on its ability to satisfy stated or implied goals (or requirements of the producers or users of the outcomes)” (Plunkett et al. 1994).

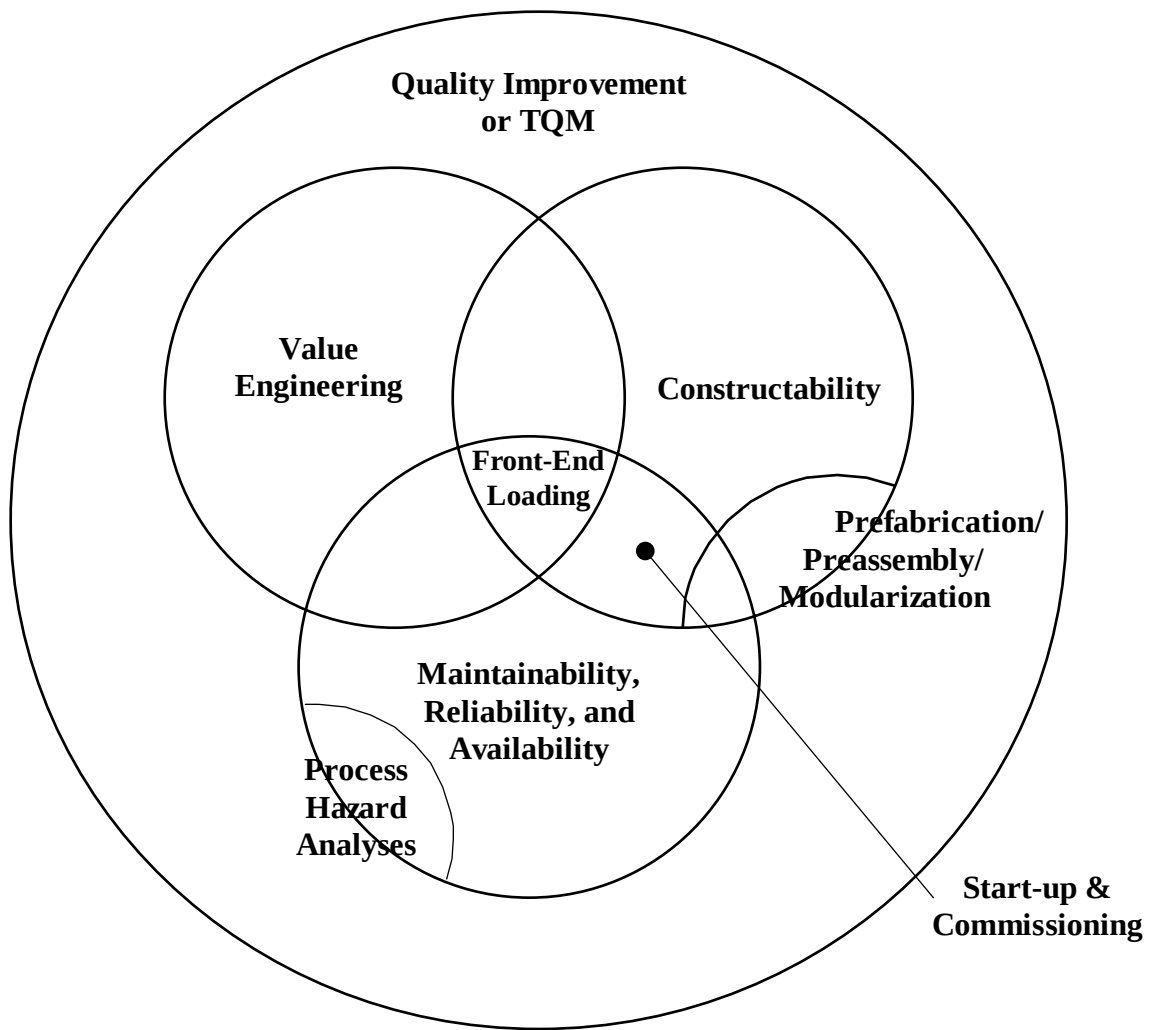


Figure 1.6: Related Industry Practices

TQM is a company-wide effort to improve performance through quality improvement. Quality improvement results are achieved through an integrated effort among personnel at all levels to increase customer satisfaction by improving performance. TQM initiatives contain elements of maintainability that could be developed or included in a formal maintainability process.

1.4.2 Value Engineering

Value engineering is a focused life cycle cost reduction effort based on a functional analysis of systems. Kavanagh et al. (1978) define value engineering as “the systematic effort directed at analyzing the functional requirements of systems, equipment, facilities, procedures, and supplies for the purpose of achieving the essential function at the lowest total (life-cycle) cost, consistent with meeting needed performance, reliability, quality, maintainability, aesthetics, safety, and fire resistance.” As maintenance cost is a key input to life cycle cost analyses, a formal maintainability process can contribute to value engineering activities in the assessment of life cycle alternatives during the project delivery process.

1.4.3 Constructability

Constructability is defined as the optimum use of construction knowledge and experience in planning, design, procurement, and field operations to achieve overall project objectives (“Constructability: A Primer” 1986). A constructability program benefits the owner, designer and contractor by optimizing the input of construction knowledge and experience during the project delivery process. Constructability programs will generally include formal reviews, open communication between owner, designer, and contractor.

Maintainability is a logical extension of a constructability program, and may be readily included as a part of the formal review process.

1.4.4 Front-End Loading

As stated earlier, the greatest opportunity to influence project outcome occurs during the planning and early design phases. The timing of maintainability input is vital to its inclusion in projects. Many suggestions are not incorporated because they are identified too late in the design cycle. Prior research by the Business Roundtable and CII has confirmed the benefits of Front-End Loading (FEL). More up-front effort results in lower capital costs, reduced time to construct, and more efficient start-up and turnover (“Pre-Project Planning: Beginning a Project the Right Way” 1994). Design for maintainability should be a part of this front-end effort.

Similar to front-end loading or conceptual planning, pre-project planning is defined as *the process of developing sufficient strategic information with which owners can address risk and decide to commit resources to maximize the chance for a successful project* (“Pre-Project Planning: Beginning a Project the Right Way” 1994). Research conducted by the CII Pre-Project Planning Research Team indicates that well-performed pre-project planning can reduce total project design and construction costs by 20% and schedule by 39%, while improving project predictability in terms of cost, schedule, and operating performance (“Pre-Project Planning: Beginning a Project the Right Way” 1994). Maintainability objectives and strategies may be incorporated during pre-project planning to allow cost-effective design for maintainability.

1.4.5 Start-up and Commissioning

The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) defines commissioning as the process of ensuring that systems are designed, installed, functionally tested, and capable of being operated and maintained to perform in conformity with design intent (HVAC Commissioning Process 1996). Traditional commissioning process is often reactive, with emphasis primarily on component checkout and start-up. Similar to a formal maintainability process, ASHRAE recommends expanding the traditional commissioning process to begin with planning and continue through design, construction, start-up, acceptance and training, and the life of the building. The recent growth of full building commissioning programs provide a means for owners, designers, and constructors to focus on delivering a building that performs as the owner intended (Tseng 1998). By beginning the commissioning process in the program and planning phase, building commissioning programs are helping to reintegrate the facility delivery process. Many commissioning issues are also maintenance issues, and the potential for adding maintainability to commissioning programs should be evaluated.

1.4.6 Process Hazard Analysis

In 1992, the Occupational Safety and Health Administration (OSHA) issued 29CFR1910.119, “Process Safety Management of Highly Hazardous Chemicals, Explosives and Blasting Agents.” This regulation requires all processes involving hazardous materials be identified, analyzed, and controlled using one or a combination of the following Process Hazard Analyses (PHA): (1) what-if; (2) checklist; (3) Hazard and Operability Study (HAZOP); (4) Failure Mode and Effects Analysis (FMEA); (5) fault tree analysis; and/or (6)

appropriate equivalent methodology. The selection of appropriate PHA techniques depends on several factors including size and complexity of the process, and current information available regarding the process.

A PHA that addresses maintenance and reliability issues is a hazard and operability study, or HAZOP. A HAZOP is a systematic review of the design and operations of critical systems. The purpose is to insure safety of a process facility by identification of hazards and/or problems that result from possible deviations from normal or designed operations. A HAZOP review answers a set of structured questions, which contain “guide words” describing process operating deviations. An example of a typical deviation is “NO FLOW.” The HAZOP team would then examine root causes of the deviation and evaluate the adequacy of safeguards in place to prevent dangerous situations. If additional safeguards are required, appropriate recommendations are made by the HAZOP team.

The opportunity exists to integrate maintainability and reliability issues into the PHA process. With the detailed information gathered and time invested in these federally mandated processes, a small amount of additional effort could produce substantial maintainability improvement.

1.4.7 Maintainability

CII defines maintainability as the optimum use of facility maintenance knowledge and experience in the design/engineering of a facility that meets project objectives (“Constructability Implementation Guide” 1993). In this context, maintainability refers to a formal process to include relevant maintenance input during all phases of the project delivery process.

Currently, industry has many different interpretations of maintainability. For some, maintainability is a quantitative measure, corresponding to the probability of performing a maintenance action or repair in specified period of time using prescribed procedures in a prescribed environment. For others, maintainability is simply the ease in which maintenance actions can be performed.

For purposes of this research, maintainability is defined as an inherent characteristic of system or product design, pertaining to the ease, accuracy, safety, and economy in the performance of maintenance actions (Blanchard et al. 1995). This definition emphasizes the ability to maintain while stressing its importance as a design characteristic.

Throughout this research *maintainability* refers to the design characteristic described above, while a *maintainability process* is defined as a formal method to incorporate maintenance knowledge and experience into the project delivery process, including specific tools to facilitate implementation such as scheduled meetings and formalized checklists. A *maintainability program* strengthens and expands the maintainability process to include required corporate technical and financial supports.

Maintenance is defined as all actions necessary to retain a system or product in or restore it to, a desired operational state (Blanchard et al. 1995). Whereas maintainability is a characteristic of design, maintenance is the result of design. The purpose of maintenance is to keep equipment or systems operating efficiently, thereby improving availability, extending equipment life, and adding value for a company.

1.4.8 Reliability

Reliability is defined as the probability of failure-free performance under stated conditions (MIL-STD-721C). Reliability pertains to the frequency of failure and the ability to function as expected. Issues affecting reliability include operating practices, design, purchasing, installation, and maintenance practices. Reliability is often improperly interchanged with availability, where reliability is only a component of availability.

1.4.9 Availability

Availability is defined as the percent of time that machinery/equipment will be operable when needed (Reliability and Maintainability Guideline 1993). Often referred to as uptime, availability improvements translate to increased production for manufacturing and industrial companies. For the general building owner, increased availability equals fewer distractions and improved worker productivity. For many companies, availability improvement is the driving force behind maintainability and reliability improvement initiatives.

1.5 INTERRELATIONSHIPS

There are multiple perspectives as to the interrelationship among maintainability, reliability, and availability. This research treats maintainability and reliability as independent concepts, both of which contribute to availability (Lamb 1995). Availability, a function of reliability and maintainability, can contribute significantly to improved profitability of a company. A graphical diagram showing their relationship is shown in Figure 1.7. As shown by the figure, inadequate maintainability directly impacts availability of the facility. Lack of

a maintainable and reliable project design results in plants being oversized with redundant systems to produce the desired level of availability.

Maintainability and reliability are often grouped together, as they deal with essentially the same design concepts from different perspectives. At the product development level, reliability and maintainability (R&M) is a science, employing mathematical analysis to quantify each parameter. Reliability analyses often serve as input to maintainability analyses. Design for maintainability is essentially designing with the end user's needs in mind. End users, i.e., maintenance staff, want a reliable, well-performing facility that he or she can maintain with reasonable effort and expense. Reliability of equipment and machinery has improved significantly over recent decades, but failure free, non-wearing parts and components are currently not available. Maintenance and maintainability will continue to have significant impact on the availability of constructed facilities and the profitability of manufacturing companies.

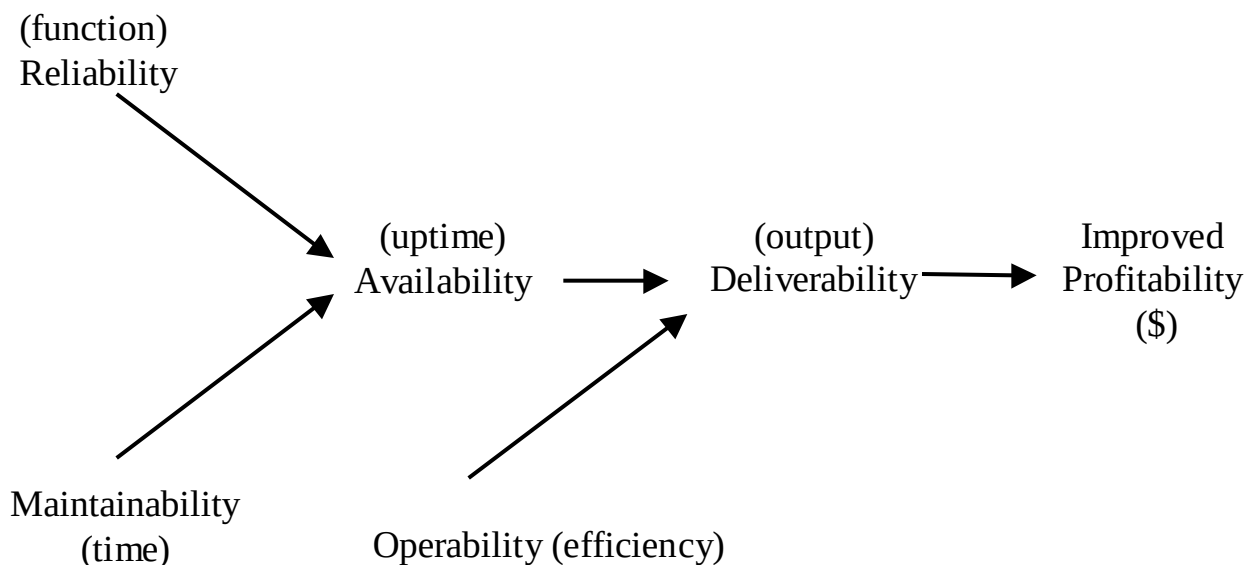


Figure 1.7: General Interrelationship of Project Definitions

1.6 SUMMARY

Maintainability presents an opportunity to improve capital investment and needs to be considered in the early phases of the project delivery process. This research contributes to CII efforts to develop a fully integrated project delivery process to provide benefits to the construction industry. Although maintainability is closely linked to reliability and availability, this research has focused solely on maintainability as it impacts design.

While Chapter 1 provided a brief introduction to maintainability, Chapter 2 describes the research methodology. Chapter 3 contains background information from the literature review and questionnaire survey. Chapter 4 describes the current state of maintainability implementation, five observed levels of maintainability in industry, and the model maintainability program. Chapters 5 and 6 describe steps and activities of the model maintainability program at the corporate and project level, respectively. Finally, practical applications, conclusions and recommendations based on this research investigation are provided in Chapter 7.

CHAPTER TWO

METHODOLOGY

2.1 PROBLEM STATEMENT

Lack of maintainability consideration during the planning, design, procurement, construction, and start-up of a project can result in decreased availability and output, increased ongoing operation and maintenance costs, and costly maintenance retrofits. A need exists to identify critical maintainability issues for incorporation into project planning and design prior to final design completion. While substantial literature is available on improving the maintenance of existing facilities, most companies lack a formal method to proactively include maintenance and maintainability into the project delivery process.

2.2 RESEARCH OBJECTIVES

The CII Maintainability Research Team adopted a format similar to constructability for its research methodology and developed model implementation process. The primary purpose of this research is to develop a model process for incorporating maintenance knowledge and experience into the planning, design, procurement, construction, and start-up of facilities. Specific research objectives include:

1. Define existing levels of maintainability in major companies;
2. Identify best practices that improve the maintainability of capital projects;
3. Develop a model process for implementing maintainability; and
4. Conduct case studies to illustrate the state of practice for maintainability.

2.3 RESEARCH SCOPE

This research investigates the process of delivering maintainable equipment, systems, and facilities as it pertains to the design and construction of capital projects. The maintainability of discrete manufactured products, such as airplanes or automobiles, is not described by this research. Given the complexity and variations of maintainability, this research focused on general practices to aid in the formalization of maintainability efforts during the project delivery process. Formal implementation of maintainability is not sufficiently mature to obtain quantitative data, and it would be difficult to develop a basis for evaluation.

The scope of this investigation is limited to the maintainability activities during six phases of the project delivery process: (1) planning; (2) design; (3) procurement; (4) construction; (5) start-up; and (6) operations and maintenance. Activities that enhance the reliability or operability of facilities are not included in this investigation, but will likely be positively influenced by maintainability activities. Although maintenance planning is an important contributor to the maintainability design process, this research does not cover the process of maintenance strategy optimization, nor recommend specific maintenance strategies and planning techniques.

Research surveyed a cross-section of companies engaged in many different types of construction, ranging from general building to petrochemical. Infrastructure, including roads, bridges, and sewer, were not included in this research due to lack of industry representatives on the research team. The organizations included in this investigation are limited to medium to large-sized companies (i.e., annual sales volume over \$20 million) currently involved in the design/construction industry in the role of owner, designer, vendor,

or construction contractor. As maintainability most directly impacts the owner of constructed projects, this research focused on owner organizations.

2.4 RESEARCH METHODOLOGY

The research methodology for this investigation is shown in Figure 2.1. The research consisted of the following six phases, with considerable overlap between each phase:

1. Synthesis of available literature;
2. Reconnaissance;
3. General survey questionnaire;
4. Data collection interviews;
5. Case studies; and
6. Definition of implementation process and best practices.

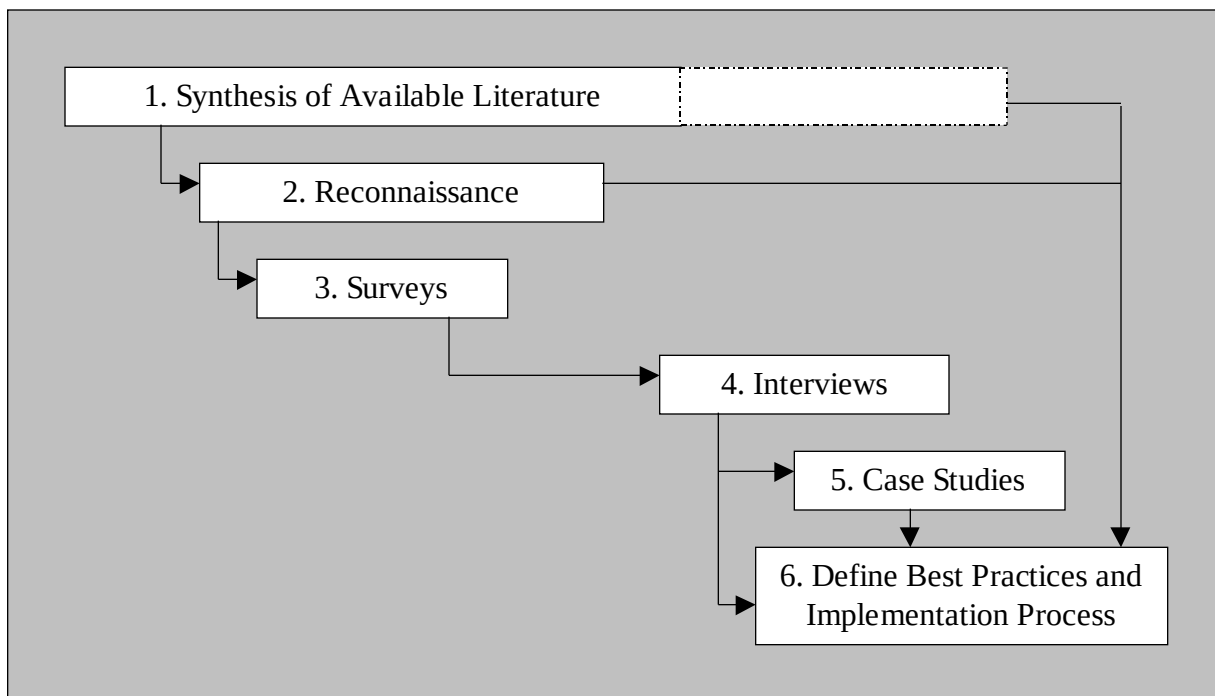


Figure 2.1: General Sequence and Overlap of Six Research Phases

2.4.1 Synthesis of Available Literature

A review of available literature provided the necessary background for the research, and shaped subsequent phases of the research. The role of maintenance is shifting from a “necessary evil” to profitability contributor, as reflected in the large number of recent “industry-driven” conference papers and journal articles related to maintenance and maintainability. Implementation-related material was limited to a handful of professional guidelines, most notably the Society of Automotive Engineers (SAE) and National Center for Manufacturing Sciences (NCMS) Reliability and Maintainability Guideline.

2.4.2 Reconnaissance

The second phase, entitled reconnaissance, provided the academic team with insight on the current challenges and opportunities facing maintenance professionals. The academic team attended two maintenance-related conferences to begin the assessment of the current state of maintainability. The first conference attended in May of 1997 was the Maintenance and Reliability Conference (MARCON) presented by the Maintenance and Reliability Center at the University of Tennessee-Knoxville. The second conference attended was the Process Plant Reliability (PPR) Conference held in Houston, TX. Reconnaissance also included early interviews with identified experts on maintainability, and site visits to a large manufacturing facility and a nuclear plant. Conference attendance and the early interviews helped identify maintainability resources and provided contacts with many of the future interview candidates.

2.4.3 General Questionnaire Survey

To gain a general understanding of the role of maintainability in industry, a questionnaire survey was circulated to construction industry participants. As the owner must lead the formal maintainability process, the survey participants were comprised largely of owner companies. This survey provided a cross-section of organizations participating in many types of projects.

The survey was developed to meet the following objectives:

1. Assess the state of design for maintainability in order to refine the research objectives and scope;
2. Accumulate recommendations for improving maintainability; and
3. Identify the most common barriers impacting the implementation of design for maintainability.

An outline of the types of survey questions is shown in Figure 2.2. A complete copy of the survey can be found in Appendix B.

Members of the CII Maintainability Research Team, also listed in Appendix B, distributed the survey to project managers, O&M managers, and maintenance technicians both within and outside their respective companies. Respondents were selected based on maintenance knowledge and prior working relationship. Of approximately 75 surveys distributed, 48 surveys were returned, a response rate of approximately 65%. Of these returned surveys, 46 surveys were from owners. Figure 2.3 shows a distribution of survey responses by type of construction.

Questions were open-ended to encourage descriptive feedback, and responses tended to be qualitative in nature. The objective of the survey was not to gather data for the purpose

of statistical analysis. The questionnaire survey enabled the research team to gain insight into maintainability implementation and further refine the research objectives and scope. The questionnaire survey also served a secondary purpose as a means to identify specific organizations and possible interviewees for the next phase of data collection, detailed interviews.

- Definitions and Interrelationships
- Maintenance Impact on Design
- Recommendations
- Costs and Measures
- Organizational Strategy
- Barriers
- Specific Examples and Opportunities for Improvement
- Work Processes
- Critical Systems

Figure 2.2: Major Sections of Questionnaire Survey

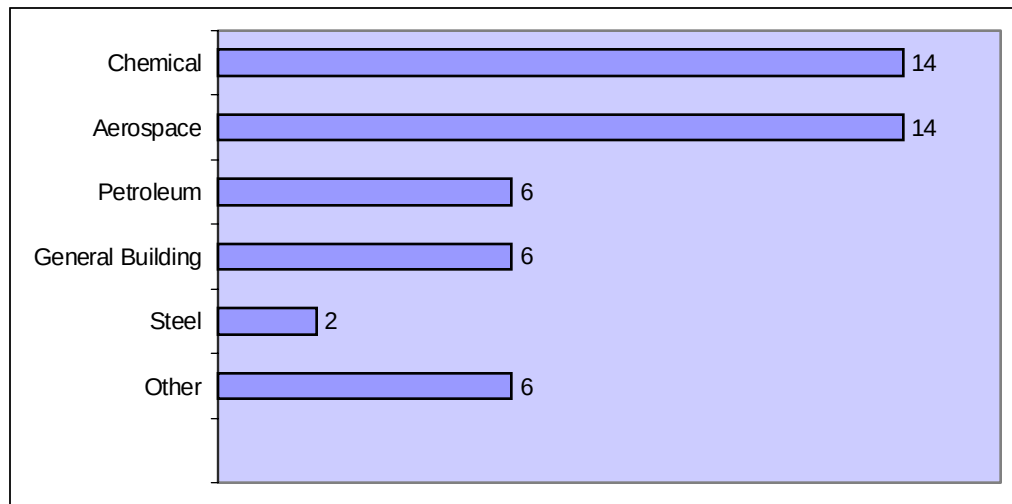


Figure 2.3: Distribution of Survey Response by Construction Type

2.4.4 Data Collection Interviews

Structured detailed (personal and telephone) interviews were the primary means of data collection. Interviewees included plant managers, maintenance managers, project managers, designers, and O&M personnel from a broad cross-section of companies. Data collection interviews focused on the end user, i.e., the maintenance staffs of owner organizations, to bring their knowledge, experience, and needs into the process. In addition to owner companies, the team met with contractor, consultant, and vendor companies to determine how they help owners meet their needs in terms of maintainability.

The basic purpose of each interview was to capture and document processes, procedures, and tools used by each company to integrate maintenance with planning and design. Specifically, the research team was looking for methods of incorporation, examples

where maintainable design was and was not used, associated costs/benefits, and future maintainability strategy.

The research team interviewed 35 organizations on the current implementation of maintainability within each company. Of these 35 interviews, 24 were formal interviews using the interview guide, while the remaining 11 interviews were completed without the interview guide. Figures 2.4 illustrates the distribution of companies interviewed by project role. The owners interviewed were largely engaged in industrial and manufacturing type construction. Industrial and manufacturing companies appear to have a keen interest in increased maintainability, given its direct impact on profitability. Data availability and maturity of maintainability efforts further pointed the research team towards the industrial sector.

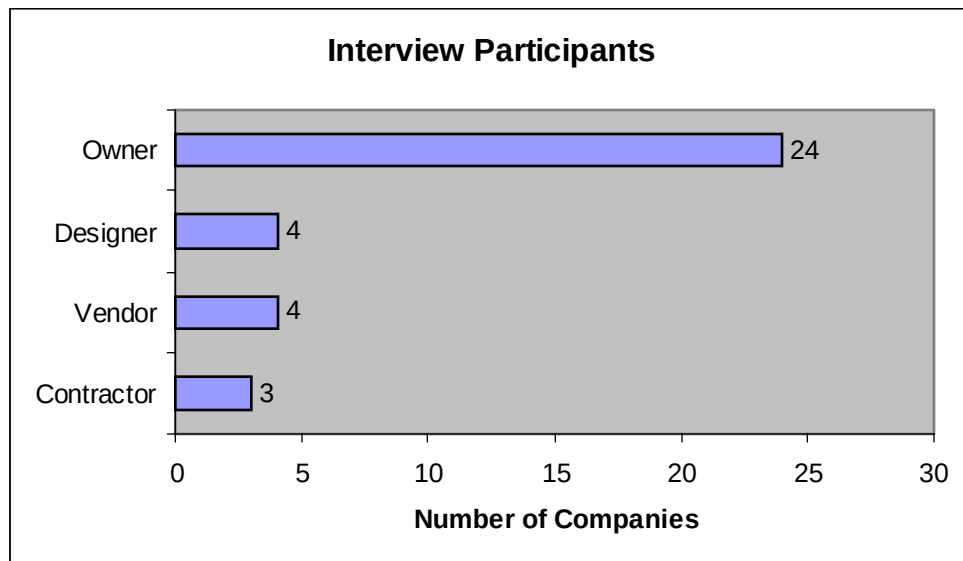


Figure 2.4: Distribution of Detailed Interview Participants by Project Role

The interview was structured into two parts: (1) corporate and (2) project. The corporate-level section focused on the role of maintainability within the organization, and identified associated work processes. In addition, costs, benefits and recommendations were part of the corporate questions. The project-level portion captured specific examples of maintainability implementation. Appendix C contains a list of the companies interviewed and a sample copy of the data collection interview guide.

2.4.5 Case Study Investigation

The research team conducted seven case studies to illustrate company programs and projects that emphasized maintenance and maintainability during the project delivery process. Case studies from several industries were chosen to provide different maintainability perspectives. The case studies describe unique challenges and opportunities for maintainability and illustrates several of the best practices contained in the maintainability model process. The case studies were conducted in parallel with the next phase, definition of best practices and implementation process. Details of the case studies are documented in a separate research report entitled “State-of-Practice in Maintainability” Russell et al. 1999.

2.4.6 Definition of Best Practices and Model Process

In the sixth and final phase, the research team synthesized and organized the research findings. Maintainability implementation, as observed in industry, is organized into five levels. The levels of maintainability implementation provide a tool for organizations to assess current maintainability approaches. The model process for maintainability

implementation contains six phases, with steps and activities associated with each of these phases. The model process for maintainability implementation were developed from reviewing recent literature, analyzing interview data, and reviewing copies of maintainability program manuals. Two intensive reviews by the CII Maintainability Research Team helped in final definition and validation of the model process.

2.5 SUMMARY

The planning, design, procurement, construction, and start-up phases can significantly affect the maintainability of the final facility. A formal maintainability process provides a method for gathering and assessing maintainability information from each of these phases for appropriate consideration during the project delivery process. Similar to constructability, it intends to identify the right questions, in the presence of knowledgeable industry professionals, to be asked at the right time—early in the project delivery process. By collecting information from recent literature, a questionnaire survey, and 35 detailed interviews, this research investigation led to the development of a model maintainability process to assist organizations in formalizing their approach to maintainability.

CHAPTER THREE

BACKGROUND

3.1 INTRODUCTION

This chapter provides the relevant background for maintainability as it applies to implementation during the project delivery process. Four basic maintenance strategies are outlined, including a description of comprehensive maintenance processes. Also, maintainability design concepts are presented, followed by general descriptions of major maintainability business and effectiveness measures. The chapter closes with an assessment of the benefits of a formal maintainability implementation process.

3.2 MAINTENANCE STRATEGIES

The project design team must develop and understand the project maintenance strategies to select the appropriate maintainability design criteria. The maintenance strategy should correspond to business objectives, and will often vary from project to project. Potential benefits and implementation of each maintenance strategy must be considered in the context of each project and owner organization. Addressing maintenance strategy during early project development and design allows maximum benefits to be accrued.

Many projects incorporate a combination of the following four maintenance strategies: (1) reactive; (2) preventive; (3) predictive; and (4) proactive. This combination is usually based on the risk and cost associated with system failure (critical equipment), problem systems, or systems with a known high maintenance cost. A reactive maintenance strategy incorporates little technology while a proactive maintenance strategy relies heavily

on evolving maintenance technologies. Each of the four primary maintenance strategies is described below.

3.2.1 Reactive Maintenance

Also known as run-to-failure, reactive maintenance waits for machinery or systems to fail before any action is taken. In run-failure-mode, no money is spent until a machine or system fails to operate, at which point the maintenance team mobilizes to repair the inoperable equipment. The major expenses associated with this type of maintenance strategy are: (1) high spare parts inventory cost; (2) high overtime labor costs; (3) high machine downtime; and (4) low production availability (Mobley 1990).

Few facilities are in a true reactive mode, as most plants use time-based actions of preventive maintenance. For non-critical equipment, reactive maintenance makes sense if the cost to replace or repair the equipment is less than the cost of monitoring and preventing problems (White 1997). A major drawback to reactive maintenance is the lack of control. Sudden, unexpected failures cause costly downtime, and a reactive approach often requires the design of redundancy. Reactive maintenance is typically the most expensive and least effective approach to maintenance.

3.2.2 Preventive Maintenance

Although there are many definitions of preventive maintenance, all preventive maintenance programs are time-driven. Maintenance tasks are scheduled at regular intervals, based on statistical analysis of failure data. Preventive maintenance tasks generally fall into one of two categories: (1) extension of asset life (e.g., greasing a gearbox) or (2) detection of

critical asset wear, with the potential for imminent failure (e.g., quarterly inspection of a pump seal) (Levitt 1996). Some common types of industrial preventive maintenance tasks are listed in Table 3.1.

Preventive maintenance can provide a useful first line of defense against early system failure, but maintenance actions are a result of time-based intervals and do not reflect the actual operating condition. The major expenses associated with this type of maintenance strategy are the following: (1) wasteful, unneeded maintenance actions; (2) introduction of problems into an otherwise normal system; unexpected or early failures; and (3) large spare part inventories.

Table 3.1: Common Preventive Maintenance Tasks (adopted from Levitt 1996)

Type of Task (1)	Example (2)
Inspection	Look for leaks in hydraulic system
Cleaning	Remove debris from machine
Tightening	Tighten anchor bolts
Operate	Advance heat control on injection molding machine until heater activates
Adjustment	Adjust tension on drive belt
Take readings	Record readings of amperage
Lubrication	Add 2 drops of oil to stitcher
Scheduled replacement or rebuild	Remove and replace pump every 5 years
Analysis	Perform history analysis of a type of machine

3.2.3 Predictive Maintenance

Predictive maintenance actions are based on equipment condition rather than time intervals. Predictive maintenance (also known as *condition monitoring*) involves continuous or periodic monitoring and diagnosis of equipment in order to predict failures, and indicates whether preventive or corrective maintenance is needed (Cost Planning and Estimating for Facilities Maintenance 1996). When predictive maintenance procedures detect potential component failure, corrective maintenance is needed to replace the component before further damage or failure results. If predictive maintenance procedures detect a deteriorating condition, preventive maintenance actions may be used to restore the system back to acceptable operating condition. The predictive maintenance technology selected for a system is dependent upon criticality and tendency/frequency of failure or deterioration. Some of the more common predictive maintenance techniques are shown in Table 3.2.

Predictive maintenance has many benefits. Elements of predictive maintenance can reduce trouble-shooting time, eliminate unplanned downtime and repair, and assure that only needed maintenance is performed. Predictive maintenance may also decrease the required spare parts inventory by anticipating future parts requirements.

3.2.4 Proactive Maintenance

Proactive maintenance uses predictive methods to diagnose equipment and systems nearing failure. However, it moves beyond diagnosis by isolating and correcting the sources of failure altogether (White 1997). The objective of proactive maintenance is to apply investigative root cause failure analysis and corrective technology to eliminate the causes of failures and extend equipment life (Hasselbaum 1993). Proactive maintenance uses the

information provided by predictive techniques to address and solve the root cause of the problem. By predicting and solving failures, proactive maintenance reduces downtime costs, eliminates recurring problems, extends machinery life, and reduces energy costs (White 1997).

Table 3.2: Common Predictive Maintenance Tasks

Type of Task (1)	Purpose (2)
Vibration Signature Analysis	Detection of increased vibration on rotating machinery that would indicate pending failure
Lubrication Oil Analysis	Monitor and trend emerging conditions on in-service machines
Infrared Thermography	Reveals hot/cold spots in equipment that may be failing
Ultrasonic Testing	Testing for small steam and air leaks; also used to check bearing degradation
Motor Current Analysis	Identification of electrical and mechanical faults in induction motors
Electrical Insulation Testing	Evaluation of insulation condition on motors and transformers